Order Flow Segmentation and the Role of Dark Pool Trading in the Price Discovery of U.S. Treasury Securities*

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October 26, 2014

Abstract

This paper studies the workup protocol, a distinctive trading feature in the U.S. Treasury securities market that resembles a mechanism for discovering dark liquidity. We quantify its role in the price formation process in a model of the dynamics of price and segmented order flow induced by the protocol. We find that the dark liquidity pool generally contains less information than its transparent counterpart, and most of the former's information value is due to workups expanding volume on the aggressive side. Moreover, we show that workups occur more frequently, but contribute less to price discovery relative to pre-workup trades, around volatile times. We also find that higher usage of workups is also associated with higher market depth, lower bid-ask spreads, and higher trading intensity. Collectively, the evidence suggests that workups are used more as a channel to encourage liquidity provision, than as a channel to hide private information.

Keywords: Dark pool; liquidity; price impact; information share; fixed income market
JEL Classification: G01, G12, G14, G18

*We thank Leslie Boni, Alfonso Dufour, Andrew Ellul, Neville Francis, Corey Garriott, Eric Ghysels, Larry Harris, Joel Hasbrouck, Jonathan Hill, Pawan Jain, Charles Jones, Pete Kyle, Bruce Mizrach, Pam Moulton, David Myers, Eric Renault, Mark Wu, Haoxiang Zhu, and participants at the MFA 2014 annual meeting, the FMA Applied Finance 2014 conference, the First Annual SEC Conference on Regulation of Financial Markets, the 10th Annual Central Bank Workshop on the Microstructure of Financial Markets, and the FMA 2014 annual meeting for helpful comments and discussions. We also thank Arthur D'Arcy, Dan Cleaves, and Stuart Wexler from ICAP for clarifying how the BrokerTec platform works, and James Greco from Jefferies for helpful information on the trading of U.S. Treasury securities. We thank Weiling Liu for excellent research assistance. Views expressed are those of the authors and not necessarily those of the Federal Reserve Bank of New York or the Federal Reserve System.

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1 Introduction

The ability to hide trading intention is important and valuable to market participants. As Harris (1997) writes: "the art of trading lies in knowing when and how to expose trading interest." Many trading venues provide features that enable market participants to manage their exposure, ranging from hidden orders to dark pools.

The BrokerTec platform, one of two interdealer electronic trading platforms for U.S. Treasury securities, is one such place where traders can conceal the extent of their trading interest. One way they can do this is through iceberg orders. An iceberg order is a limit order that displays only a portion of the order quantity, called the display size, with the rest invisible to the market. The hidden quantity is revealed only gradually to the market as the displayed size is fully executed and the next installment becomes visible.

A second way traders can conceal the extent of their trading interest is through the workup process. A workup is a protocol that automatically opens after the execution of each market order. During the workup window, any interested market participants can transact additional volume at the same price established by the initial execution, as long as counter trading interest exists. Workups thus provide traders the option to submit orders of smaller size than desired, and then to increase the size when the workup opportunity opens.

It is intriguing to observe that iceberg orders are used sparingly in this market as compared to workups, even though the former has higher execution priority. On average, less than 5% of transactions involve execution against iceberg orders, whereas volume expansion through the workup protocol happens 49-56% of the time for the on-the-run 2-, 5- and 10-year notes and nearly 40% of the time for the 30-year bond.

The economic significance of the workup protocol is demonstrated not only by its frequent usage, but also by the magnitude of the expanded volume. On average, worked-up trading volume accounts for 43-56% of total daily trading volume, depending on the security being traded. In transactions with a workup, the worked-up dollar volume accounts for over 60% of total transaction volume. Collectively, these statistics show that the workup protocol uncovers a significant amount of market liquidity that is not ex ante observable to market participants. More importantly, the workup feature relates to a salient fact about the Treasury limit order book: market orders rarely walk up or down the book, at least for the on-the-run securities examined in this paper.

The fact that a significant portion of market liquidity is only revealed during the workup process, while the price is fixed, raises an important question about its role in the price formation process. Does this portion of order flow carry information? If so, how does it compare to the "transparent" part (i.e., the execution of the initiating market order)? Up until now, the literature on price discovery of U.S. Treasury securities, such as Brandt and Kavajecz (2004), Green (2004), Pasquariello and Vega (2007), and others, has been concerned only with the informational role of generic order flow. Implicitly, it is assumed that the trade flow is homogeneous and that the portion transacted in the pre-workup stage has the same impact on price dynamics as that in the workup phase.

The theoretical literature on dark trading suggests that this is not the case. For example, Zhu (2014) argues that the different execution probability of orders in transparent versus dark venues for informed versus uninformed traders likely steers informed traders to the transparent venue and uninformed traders to the dark venue. In contrast, Ye (2012) predicts that informed traders are more likely to hide their information in the dark, thereby reducing price discovery. Although arriving at opposing predictions, both models suggest that the information content of the transparent and dark parts of trading is different as a result of how informed traders optimize their exposure strategy to exploit their information advantage.

It is also not realistic to study the information role of trades in this market without recognizing or appreciating that the workup feature is an integral part of the trading process and a useful device for order exposure management. Accordingly, it can alter traders' optimization outcomes and decisions, as compared to a hypothetical market setup in which this option is not available. For example, aside from choosing between market and limit orders, traders also have choices over the exposure of their trading intention. If it is a limit order, the submitter can 1) display the full order size, 2) submit the full order size but hide part of it from view (i.e., submit an iceberg order), or 3) submit a smaller sized order and wait to expand the order size if and when the order is executed and the workup is open. Likewise, if it is an aggressive order, the available choices are: 1) submit the full sized market order for immediate execution, 2) submit a smaller sized market order and hope to increase the volume in the ensuing workup, or 3) wait for a workup at the right price to trade. The fact that workups are used so frequently in this market speaks for its importance in traders' decision making.

The workup protocol, by providing traders with an option to expand order size beyond the initially submitted level, can be beneficial to informed traders in multiple ways. For example, an informed trader may choose to submit a limit order of less than the intended quantity to minimize information free-riding by others, knowing that he has the opportunity to increase the size when the order is aggressed against (i.e., executed by a market order). These are the “informed liquidity providers” as discussed in Boulatov and George (2013). Alternatively, an impatient informed trader with a large trading interest may submit a market order small enough to execute at the best price, and then search for further counter trading interest during the subsequent workup at the same price, without having to walk deeper into the book.

The informativeness of the workup order flow, however, also depends on the actions of the uninformed. If they behave in the sense of Zhu (2014), or if they are reactive traders who act upon the lead of others as described in Harris (1997), the uninformed are more likely to trade in the workup stage, thereby reducing the informativeness of workup order flow. Likewise, the uninformed can participate in the market on the liquidity provision side, and thus volume expansion of limit orders during workups is not necessarily information motivated.

Given the mixed guidance from theory, the informativeness of workup order flow in practice is an open question. The paper aims to address this question and thereby provide a more complete picture of the price formation process of U.S. Treasury securities. We do this by separating order flow into the trade initiation (or “transparent”) part and the workup (or “dark”) part, and quantifying how these respective components contribute to price discovery.

Based on transaction data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities from the BrokerTec platform over the period 2006-2011, we find that workup order flow is informative, albeit less informative than trade initiation order flow. Workup order flow is most informative for the 2-year note, explaining about 17% of the total variation of the efficient price update. The 5- and 10-year counterparts explain between 7-8% of the variation of the efficient price. It is only 1%, however, for the 30-year bond, indicating that traders in this maturity segment do not opt for the workup as a channel to exploit their information advantage. Price discovery in the 30-year segment is most attributable to public information, which accounts for over 80% of the variation of the efficient price update. Our analysis also illustrates the importance of recognizing the information segmentation of order flow due to the workup protocol. We show that the impact of actively initiating a trade and the share of trade-related information are underestimated if one does not consider the segmentation.

Except for the 2-year note where the workup order flow is slightly more informative, our information share analysis generally supports the predictions of Zhu (2014) in that the transparent part of order flow is more informative than the dark part. Our evidence is also consistent with Comerton-Forde and Putnins (2013) who study dark trading and price discovery of stocks traded on the Australian Stock Exchange and find that the order flow that migrates to the dark is less informed, but not completely uninformed. Intuitively, informed traders with a short-lived information advantage may choose to initiate a trade and realize their information advantage quickly, since the potential of not finding a counter-party during the workup can make the workup option costly (e.g., forgone information value). This is strongly supported by our result that the transparent (or "lit") part of the order flow becomes relatively more informationally important on high volatility days, when adverse price movements could fasten the expiry of information.

Although less informative than the trade initiation flow, the workup process is responsible for the discovery of a significant portion of market liquidity and plays a non-trivial role in price discovery. It is therefore important to understand what factors might predict the use of a workup following a market order execution and the extent of the volume expansion. We employ a logistic regression model for the probability of a workup as a function of hypothesized determinants, including prevailing order book depth on the same side, spread, depth on the opposite side, price volatility and a set of control variables. We employ a Tobit model censored at the zero lower bound to capture the effects of the same set of explanatory variables on workup volume, since volume is zero for non-workup transactions and strictly positive for those with a workup. We find that, in general, a workup is more likely and expands greater volume when the market is deep, upon the discovery of hidden orders, and around the times of high trading intensity, volatility and workup activity. Outside New York trading hours, workups occur less frequently and discover less volume.

Despite workups being an unusual and economically important trading feature in the U.S. Treasury market, academic research specifically on the workup process and its implications on market participants' trading strategies is limited. The paper closest to ours is Boni and Leach (2004) who investigate the workup protocol using GovPX data for October 1997. At that time, interdealer trading was still conducted over a network of voice-assisted interdealer brokers (IDB). GovPX collected and disseminated market data from five such IDBs. Each of the IDBs maintained its own limit order book, facilitated trades and mediated quantity negotiations beyond the quoted depth. Boni and Leach hence characterize this market as one in which limit orders are "expandable".[1] They find that this expandability option helps limit order traders reduce costs associated with information leakage and adverse execution of stale limit orders.

Dungey, Henry, and McKenzie (2013) account for the workup feature in their model of trading intensity on eSpeed, the other electronic trading platform. They find that the duration of a workup significantly fastens the arrival of the next market order. They interpret this result in light of Easley and O'Hara (1992)'s theory that market participants infer the presence of informed traders by the time between trading events. They thus suggest that workups provide information to the market.

Adding to this literature, our paper is the first to consider the segmented order flow due to the workup protocol and formally quantify the informativeness of the dark trade flow in comparison with that of the transparent trade flow in a well defined microstructure model of the dynamics of price and order flow. The paper therefore provides a more complete picture of how the trading process with the embedded workup feature – a distinctive microstructure feature of secondary trading in U.S. Treasury securities – affects the price formation process of these securities.

Furthermore, we extend the model used by Boni and Leach by exploring and controlling for a wider range of potential determinants of workups as suggested by the literature on dark pool trading and hidden liquidity. The extension is also valuable because the workup protocol as prevailing on BrokerTec differs considerably from its historical precedent as studied in Boni and Leach, making it important to reevaluate the workup protocol under its current structure.

Our contribution goes beyond a study of a specific microstructure feature of the U.S. Treasury market in two important ways. First, the paper is a timely addition to the literature on dark

[1] BrokerTec's workup protocol differs from that of voice-assisted brokers in several ways. First, quantity negotiation on BrokerTec is governed by a set of precise rules stipulating the window of opportunity for workup trades, replacing the role of human brokers in going back and forth between counterparties working up the size of a trade. Second, as explained by Boni and Leach, with the voice-assisted brokers, when a limit order on an IDB's book is aggressed by a market order, the IDB gives the limit order's submitter the right-of-first-refusal to provide additional liquidity, even when there are other limit orders at the same price in the book. This exclusivity was completely eliminated on BrokerTec in early 2006, making workups immediately open to all market participants following the original trade(s) on a first come, first served basis (source: "System and Method for Providing Workup Trading without Exclusive Trading Privileges", patent number US 8,005,745 B1, dated August 23, 2011). Furthermore, the expanded volume can come from either the aggressive or passive side during a workup so that the workup is no longer confined to expanding only limit orders. Recently, BrokerTec instituted a new rule that allows for a workup to terminate prematurely if there is sufficient trading interest at a better price point (source: "System and Method for Providing Workup Trading", patent number US 7,831,504 B1, dated November 9, 2010).

pool trading. There is currently an active discussion among researchers and policy makers on the effects and implications of dark pool activities on market quality and welfare (see for example Degryse, de Jong, and van Kervel (2014)). On the one hand, the existence of undisplayed liquidity compromises pre-trade transparency and can potentially harm less informed traders. On the other hand, supporters of dark pool trading mechanisms point to greater market liquidity and better execution quality for trades, especially for large trades that can be executed without causing negative price impact. Complicating matters, dark pools come in many forms. It is therefore important to understand these various types of dark pools in different market setups and how their specific operationalization might affect trading behavior and patterns.

The workup process in the Treasury market resembles a crossing network, a common form of dark pool.[2] As in a crossing network, workup trades are matched on a first come, first served basis at a reference price derived from the initial marketable order execution. While a crossing network is a common form of dark pool used in many equity trading venues, not much is known about this form of dark pool in a fixed income market setting. We find that volatility tends to generate more workups, but that those workups tend to be less informative, suggesting the value of this crossing network in protecting traders against adverse price movements. In general, the amount of private information hidden in this Treasury dark pool is quite small, easing concerns that the dark pool could harm less informed traders.

The second direction in which our findings might be valuable is in the area of market design response to high frequency trading. High frequency trading, or computer-driven trading in general, has increased significantly over the last few years – a trend dubbed "rise of the machines" in Chaboud, Chiquoine, Hjalmarsson, and Vega (2013). This has spurred debate on whether the competition for speed has resulted in socially wasteful investments in trading technology. Budish, Cramton, and Shim (2014) argue that a continuous limit order book is a flawed market design in the face of increased high frequency trading. They propose frequent batch auctions as a way to

[2] Buti, Rindi, and Werner (2011b) characterize dark pools as having "limited or no pre-trade transparency, anonymity and derivative pricing." The workup process has precisely these characteristics. First, the workup process enables execution of additional trading interest not observed by market participants before each transaction. Second, all trades through interdealer brokers in the Treasury market are anonymous. During the allowable workup time window, market participants can send in orders, which are then matched by the system. Any unmatched volume is held in the system waiting for subsequent counter trading interest in the workup. Third, the price for these workup executions derives from the execution of the initial market order that triggers the workup. We thank Joel Hasbrouck for this insight.

eliminate technical arbitrage opportunities prevailing at very high frequency and to slow down the arms race. Whether this is a feasible proposal is outside the scope of our paper, but the important takeaway from this discussion is that there is a continual need to devise new market design features to keep up with changing trends in trading, and to understand the implications of those features.

The BrokerTec market setup fits right into this discussion via its unique design. Its market structure features an interesting mix of continuous auction (the limit order book) and periodic call auctions (workups). These periodic call auctions open and close after every marketable order execution, allowing for the discovery of additional liquidity. This can potentially help slow down activities of high frequency traders and give other traders an opportunity to trade at a given price point. Viewed from this angle, the workup protocol might be one possible design response to high frequency traders and the arms race discussed above. Our empirical results readily provide a glimpse of the implications of such a market feature on price discovery. Even though price is fixed during workups, activities during the workup window do contribute to price discovery, mostly by trades that expand the aggressive side. Nevertheless, the extent of this contribution is small in comparison to that of initiating trades that lead to workups.

The paper is organized as follows. Section 2 describes the workup process in detail, discusses the data used for the analysis and presents key stylized facts concerning workups. Section 3 presents a microstructure model for the dynamics of segmented order flow and price, and analyzes the price impact and informativeness of the respective components of order flow. In Section 4, we model and discuss the dependence of workup probability and workup volume on market condition variables. Finally, Section 5 summarizes our key empirical findings and concludes the paper.

2 The Workup Process

2.1 Market Overview

This paper focuses on the interdealer trading segment of the secondary market for U.S. government securities.[3] Trading in this segment, especially in the on-the-run securities, occurs mostly on

[3] In this interdealer market, the majority of participants are Treasury securities dealers, some of whom are primary dealers with obligations to participate in Treasury securities auctions. The paper uses the term "dealers" interchangeably with "traders" and "market participants", even though there are other participants in the market such as hedge funds.

two electronic trading platforms, BrokerTec and eSpeed (Barclay, Hendershott, and Kotz (2006)). Comparing BrokerTec trading statistics with those reported by other studies using eSpeed data (e.g., Dungey, Henry, and McKenzie (2013) and Luo (2010)), we observe a greater market share for BrokerTec across all four securities considered.[4] Dunne, Li, and Sun (2011) compare price discovery on the two platforms using non-contiguous data for 2002, 2004 and 2005 and conclude that more price discovery takes place in the more active but less transparent BrokerTec platform.[5]

Both BrokerTec and eSpeed operate as electronic limit order markets with no designated market maker. Liquidity supply comes from the limit order book, which is a collection of limit orders at various price levels submitted by market participants. Execution of orders follows the price and time priority rule. Our empirical analysis is based on BrokerTec data and our discussion of how the market works is for the BrokerTec platform.

In submitting limit orders, market participants can choose to display order size either partially (iceberg orders) or completely. If the former, the rest of the order size is not observable by other market participants. As the displayed portion is exhausted through trading, the next installment of the order quantity becomes displayed. This process continues until the total order quantity is completely executed. It is noted that the hidden portion of an iceberg order takes precedence over the displayed part of orders queuing behind it at the same price level.[6]

Traders demanding liquidity can send in market orders. Market orders must be priced. That is, beside the order quantity and whether it is a purchase or sale, traders must specify a price.[7] When a market order arrives, it is matched with one or more limit orders standing on the opposite side at that price (or better), starting with the displayed depth before executing against any hidden depth. For example, consider a market order to *buy* \$100 million at a price of 25580 when there is \$30 million available at the best ask price of 25578 and another \$100 million at 25580.[8] The first \$30 million of the order will be matched with limit sell orders at 25578. Assuming there is no

[4] Comparison of BrokerTec and eSpeed activity for the same sample periods and trading hours shows that the market share of BrokerTec ranges between 57% to slightly over 60% for the 2-, 5- and 10-year notes. The market share in the 30-year bond is slightly lower, but it is still over 50%.

[5] These authors note that eSpeed does not have hidden orders, whereas BrokerTec allows such orders and is thus considered as having less pre-trade transparency.

[6] This is different from other market setups in which the hidden part of an iceberg order goes to the end of the queue when it becomes visible.

[7] In essence, they are marketable limit orders. In this paper, we use the terms "market orders", "marketable orders" and "aggressive orders" interchangeably.

[8] In the BrokerTec database, prices are stored in 256th's of one percent of par value. The prices used in the example translate to 99.9140625 (25578/256) and 99.921875 (25580/256).

hidden depth at that price, the remaining \$70 million will be executed at 25580. If a limit sell order is an iceberg order, then upon the execution of the displayed portion, the next portion becomes visible and available for execution. Continuing with the above example, assume that there is \$15 million hidden depth at the best ask price of 25578. The market order will be executed as follows: \$45 million at 25578 (\$30 million displayed + \$15 million hidden), and \$55 million at 25580.

The execution of a market order is just the beginning of a transaction. Once all possible matches have been made (against displayed and hidden depth in the book, if any), the market then enters into a workup process during which additional volume at the same price can be transacted, until there is no further trading interest. Using the example above, once the original buy order execution of \$100 million is complete, the workup protocol opens at the last price of 25580. As described in one of BrokerTec's patent documents relating to the workup protocol, the whole process is conceptually "a single deal extended in time".[9] The protocol is discussed in greater detail in the next subsections.

Finally, it is worth noting that BrokerTec charges a fee for order execution, and that this fee is trader-specific and not order-type specific.[10] That is, a trader is charged the same fee whether his order is a limit or a market order, and whether his order is executed in the pre-workup or workup stage. Therefore, for each trader, the fee is not a consideration when it comes to the choice of order type and exposure. However, traders with different levels of trading activity might be subject to different fee structures.

2.2 The Workup Process

The workup is a distinctive feature of trading in U.S. Treasury securities. The process automatically opens after each market order execution, giving all market participants the chance to transact additional quantity at the last price. The ability to transact additional quantity during the workup process thus enables traders to submit orders of smaller size than their desired quantity, and then expand the quantity during the workup. The workup protocol therefore offers a higher degree of control over if and when to trade the additional needed quantity, whereas iceberg orders are subject to the risk of being adversely executed before the order submitters have a chance to modify or cancel. However, the cost for the traders hoping to expand volume in a workup is that the incremental

[9] "System and Method for Providing Workup Trading", U.S. Patent No. 7,831,504 B1, dated November 9, 2010.
[10] The exact fees are proprietary and we do not have information on these fees.

quantity they expect to transact may not materialize if counter trading interest is lacking. Thus, for those who need immediate execution, non-execution risk can be a major deterrent to using workups.

Historically, the workup process consisted of two distinct phases: 1) the private phase, which gave an exclusive right of first refusal to the original parties to the transaction, and 2) the public phase, which is open to all other market participants. However, in 2006, the private phase was replaced by a public phase, making the workup a double-public process. As a result, a transaction will progress straight to the first public workup phase after all possible matches with the limit order book have been completed. During this phase, additional trading interest can come from either side of the market, and these extra trades are conducted on a first come, first served basis.

The first public workup phase is open for a pre-specified duration (it was 4 seconds from early 2006 until July 2011 when the duration was shortened to 3 seconds). If there is no trading interest, the workup process automatically expires at the end of this duration. However, if and when a new execution occurs during this time window, the second public phase commences and a new duration opens up. It is then re-settable each time a new execution occurs. This protocol allows the workup to last as long as there is trading interest at the same price point, or to terminate after a predetermined time period if no such interest exists so that the market can move forward.

All trades during a workup – triggered by the initial execution of a market order – are executed at the same price as that of the original market order. As the extra liquidity discovered during the workup process at a given price is not known to the market *ex ante*, the workup process can be likened to a dark pool trading mechanism. More precisely, it resembles a crossing network, in which the last price serves as the reference price for the execution of additional trades during the workup.

We treat the whole process from the initial execution to the expiration of the ensuing workup as a single transaction. Each transaction can involve multiple trades or order matches. For example, a market order can execute against multiple (smaller sized) limit orders. Each of these executions is recorded separately in the database and is referred to as a trade, an order match, or an execution. We refer to those trades (or matches) that happen before the workup as pre-workup trades. Other interchangeable terms for "pre-workup trades" include "transparent trades", "lit trades", "normal trades", and "non-workup trades". Those that occur during the workup phase are referred to as workup trades or "dark trades".

2.3 The BrokerTec Data

The tick data from BrokerTec contains records of all market activity, from limit order submission, cancellation, and modification, to matching with incoming market orders, time-stamped to the millisecond. We extract information on all trading activity from this raw, comprehensive database. There is a flag each time a market order arrives. Once automatic order matching with the limit order book completes, another flag indicates the commencement of the workup phase. Finally, when the workup expires, it is also flagged in the database. As a result, we are able to identify the complete sequence of activities pertaining to each transaction.

The trade direction of the original market order, i.e., whether the aggressive side is a buy or a sell, is also recorded, thus providing unambiguous signing of all pre-workup trades. The signing of trades executed during the workup process warrants some further discussion. BrokerTec considers these trades as an extension (time-wise and volume-wise) of the original execution. Hence, workup trades occur at the same price and follow the same trade direction as that of the original execution, even though they can arise from either side of the market. For example, if the original aggressive side is a buy, then the buy side remains the aggressive side in the workup, and the sell side is the passive side. Therefore, there is no confusion as to the signing of workup trades.

After identifying the sequence of activities for each transaction, we aggregate information for the transaction, separately for the pre-workup and workup phases. In particular, we count the number of trades as well as the total dollar volume exchanged in each respective phase. Furthermore, if there is execution against the displayed portion of an iceberg order resulting in the exposure of new depth, we mark the transaction as involving execution against an iceberg order.

The transaction data is then combined with the limit order book snapshots prevailing just before and after each transaction. The limit order book is reconstructed from the raw BrokerTec data by cumulating changes to the order book from the beginning of each trading day. Combining the limit order book data with the transaction data provides a complete picture of the market at each transaction, facilitating our empirical analysis of factors that are related to workup activities.

Our sample covers the period from 2006 to 2011. We focus the study on the on-the-run 2-, 5-, 10- and 30-year fixed principal securities. The on-the-run 3- and 7-year notes are excluded from our analysis due to discontinuity in issuance. Issuance of the 3-year note was suspended between

May 2007 and November 2008. Issuance of the 7-year note was suspended between April 1993 and February 2009. We do not have access to comparable tick data for any other Treasury securities.

2.4 Univariate Analysis of Workup Activities

2.4.1 Trading and Workup Activities

An overview of market trading activity is presented in Table 1. Panel A shows the average daily total trading volume and number of transactions. The 2-, 5- and 10-year notes have comparable trading volume in the $30-35 billion range. This far exceeds the average of $5 billion in daily trading volume for the 30-year bond. The number of transactions per day varies across securities, from the low 1,000's range for the 2- and 30-year securities to over 2,600 for the 5- and 10-year notes. It follows that trading in the 2-year note tends to occur in much larger size than is the case for other securities.

We find that market participants utilize the workup protocol in 49-56% of transactions for the notes, but only 39% of transactions for the 30-year bond. The workup share of dollar volume happens to be similar to the share of transactions with workups, ranging from 48-56% for the notes, but only 43% for the bond.

To complement the sample average statistics on workups, we further examine the time series trend of the use of workups in Figure 1. There is a modest increase in the use of workups from early 2006 until late 2008, when the workup shares of transactions and order flow drop before partially bouncing back in early 2009. The patterns have been fairly stable since then, except for a sharp decline in workups for the 2-year note, to about 40% in the second half of 2011. Also evident from the figure is that workups in the 30-year bond happen less frequently that they do in the notes, but expand proportionally greater volume when they do occur.

Table 1, Panel A also reports the probability of transacting against an iceberg order for comparison, and illustrates that workups are used much more frequently in this market. The chance of hitting/taking an iceberg order is only around 4%, which is less than one tenth the probability of having a workup. Additionally, the workup protocol, in providing traders with the opportunity to expand transaction volume at a given price, likely contributes to the finding that transactions in these securities almost never execute at multiple prices, beside the fact that the market is often very deep relative to the size of most market orders.

Further details at the transaction level, with and without workups, are presented in Panels B and C respectively. We discuss first the transactions with workups (Panel B). This panel shows that the 2-year note has the largest dollar volume per transaction when there is a workup, at about $42 million. This is more than double the size of a transaction in the 5- or 10-year notes and about eight fold the size of a typical transaction in the 30-year bond. The number of trades per transaction is just below 10 for the notes and about 4 for the 30-year bond. Roughly two thirds of trades occur in the workup phase.

Panel C shows that transactions without workups tend to be much smaller in size, in terms of both dollar volume and trade count, than those with workups. Moreover, transactions without workups tend to be somewhat smaller than even just the pre-workup portions of transactions with workups. For example, the 2-year note's average transaction size without a workup is about $12 million, compared with a $16 million pre-workup size and $42 million total size for transactions with a workup. This is consistent with Harris (1997)'s reasoning that small traders are usually not concerned with exposure issues, and importantly, the small size is of little interest to other traders. Small trades can also be absorbed more easily by outstanding limit orders. Consequently, small market orders are more likely to be executed without a workup.

Finally, it is useful to compare workups on BrokerTec with those on eSpeed as reported in Dungey, Henry, and McKenzie (2013) for the period from January 2006 to October 2006. BrokerTec's greater market share in terms of total trading volume masks the fact that trading is slightly less frequent on BrokerTec, but that an average transaction has a much greater size.[11] The likelihood of workups is a few percentage points higher on BrokerTec than on eSpeed. However, BrokerTec workups typically discover a slightly smaller proportion of transaction volume. Accordingly, the overall share of workup volume does not differ greatly between the two platforms.

[11] Our comparison shows that an average transaction in the 2-, 5- or 10-year note is over 40% larger on BrokerTec than on eSpeed, while that in the 30-year bond is about 14% larger.

2.4.2 Intradaily Pattern of Workup Usage

Figure 2 plots the probability of workup over the course of a typical trading day, from 18:30 of the previous day to 17:30 of the current day (Eastern Time – ET).[12] The figure shows that workups are most active between 8:30 and 15:00. Outside of New York hours, workup activity is markedly lower, with a mild increase occurring around the start of London trading at 3:00.

The lower workup usage in the overnight hours may be related to the low overall level of activity during the overnight hours (e.g., Fleming (1997), Fleming, Mizrach, and Nguyen (2014)). The workup protocol requires more active monitoring of market activity and exercise of judgment on the part of traders, which are less likely to occur during these hours. Moreover, workups during the off hours are less likely to be filled due to lower market participation and hence lower chance of meeting counter trading interest.

2.4.3 Workups and Order Flow

There are further interesting stylized facts relating to trading and workups. Table 2 reports several pairwise correlations of interest. First, the signed order flow imbalance, measured by net order flow as a percentage of total order flow for each day, is only weakly related with workup usage, with the absolute correlation coefficient under 0.05 for three out of four securities. However, the absolute order imbalance shows a much stronger correlation with the use of workups: except for the 30-year bond, the correlation coefficient is in the negative 0.2-0.3 range. That is, we tend to see relatively more workup activities on days when the market is balanced than when it is one-sided, whereas the direction of the imbalance does not matter much. This observation can be interpreted in light of Sarkar and Schwartz (2009)'s notion of market sidedness as an indication of asymmetric information, as informed traders tend to collect on one side of the market. If so, they are more likely to initiate trades to exploit their information advantage quickly, as opposed to trade in workups or post expandable limit orders.

Secondly, workups tend to be used relatively more frequently on more volatile days. This is

[12] Fleming (1997) provides a description of the global trading day in U.S. Treasury securities. It starts at 8:30 local time in Tokyo, which is 18:30 EST (or 19:30 EDT) the previous day (Japan has not adopted daylight saving time). Trading then passes on to London at 8:00 local time, i.e., 3:00 ET. New York trading then starts at 7:30 and continues until 17:30. Statistics for the hour from 18:30-19:30 of the previous day are based on the periods over which the U.S. is on standard time.

illustrated by the strong positive correlation coefficients across the four securities, ranging from 0.26 for the 30-year bond to 0.54 for the 2- and 10-year notes. Finally, we also observe positive first order auto-correlation in workup activities, consistent with a liquidity externality effect of workup trades as predicted by Buti, Rindi, and Werner (2011a). Specifically, increased workup activities imply that it is relatively easier to find counter trading interest in workups, thereby increasing the execution probability, and hence attractiveness, of workup orders.

2.4.4 Direction of Workup Volume Expansion

Given the current workup setup on BrokerTec, any trader from either side can join an open workup. Accordingly, volume can be expanded from either the limit order book side, or the aggressive side of the transaction. It is informative to examine the direction of volume expansion in a workup because it is ultimately linked to the degree of pre-trade transparency with respect to liquidity: the level of available liquidity market participants can see before a trade versus what actually shows up in the trade. Moreover, workup volume expansion from the aggressive side suggests the extent to which other traders follow the lead of the initial aggressive trader. It provides an indication for the amount of inactive trading interest which gets revealed only when someone else has initiated a trade. Most importantly, the ability to work up volume on either side of a transaction is one of the key features that differentiates BrokerTec's workup protocol from its voice-assisted predecessor.[13]

Figure 3 provides an analysis of the mix of workups with respect to the direction of workup volume expansion. We classify workups into three categories: 1) expanding volume on the aggressive side only, 2) expanding volume on both sides, and 3) expanding volume on the passive side (or both). Specifically, if a transaction's total volume is not greater than the available depth, all of the workup trades must have come from the aggressive side (category 1). If, instead, a transaction's total volume is greater than the available depth, the limit order book must have been expanded during the workup. Whether or not the aggressive side is also expanded can be determined by examining the pre-workup volume. If the pre-workup volume is less than the available depth, it is clear that the

[13] This is also where BrokerTec's workup protocol differs from eSpeed's. As described in one of eSpeed's patent documents, a market order needs to be sufficiently large to exhaust all displayed passive orders at the best price in order to trigger a workup, during which the initial parties to the trade are granted the right of first refusal (source: "Systems and Methods for Trading", patent application publication number US 2004/0210512 A1, dated October 21, 2004). That is, small-sized market orders do not trigger workups and thus the volume expansion on only the aggressive side is not possible under eSpeed's workup protocol.

workup also expands the aggressive side (category 2). However, if the pre-workup trades completely wipe out the available depth, it is less clear whether the aggressive side is also expanded during the workup, although the passive side is certainly expanded (category 3). Accordingly, the sum of categories 1 and 2 provides a lower bound for the fraction of workups that expand the aggressive side, whereas the sum of categories 2 and 3 equals the percentage of workups that involve expansion on the passive side.

As can be seen from the figure, there is a cross-maturity variation in the direction of workup volume expansion. For the 2-year note, the majority of workups (at least 73%) expands the aggressive side, including the 53% of workups that expand only the aggressive side. Workups that expand the passive side occur 47% of the time. On the other end of the maturity spectrum, for the 30-year bond, workups mostly expand the limit order book (78%). Instances where only the aggressive side is expanded account for only 22% of workups. The 5- and 10-year notes are in the middle, with nearly 40% of workups expanding the aggressive side only, 23% expanding both sides, and another nearly 40% expanding the passive side or both.

These statistics show that aggressive workups are common for the notes (especially the 2-year) but not for the 30-year bond. In addition, workup trades often come from both sides within a given transaction, accounting for 20% or more of workups in the notes. Taken together, the evidence demonstrates how the workup protocol on BrokerTec's electronic trading platform differs markedly from the earlier workup protocol described in Boni and Leach (2004).

In order to see if the workup mix is sensitive to different times of day and market conditions, we also analyze the direction of workup volume expansion over different trading hours, on volatile days versus tranquil days, and on days with extreme net order inflow versus net order outflow. In general, the patterns are similar and thus, for brevity, not reported. One notable finding from our sensitivity analysis is that traders in the notes tend to expand limit orders more often on extremely volatile days. Together with the evidence documented earlier that workups are used more frequently on volatile days, this finding is consistent with Boni and Leach (2004)'s conclusion that limit order expandability is helpful to limit order traders as it helps them reduce pick-off risk and information leakage associated with posting large limit orders during volatile times.

3 Informational Value of Workup Trades

We proceed to specify a microstructure model for the dynamics of price and order flow, built upon the general framework described in Hasbrouck (2007). The notable feature of our model is that it accounts explicitly for the segmentation of order flow due to the workup feature, as theory suggests that the transparent and dark components of order flow likely have different information values. From this model, we derive a structural VAR representation in (irregular) trade time to be estimated using the data. We then discuss the empirical implementation and findings of the model.

3.1 A Microstructure Model of Price and Trade

Let t index the t^{th} market order. We distinguish events occurring during the pre-workup and workup phases of the t^{th} transaction by the subscripts t^- and t^+ respectively. P_{t^-} denotes the best bid ask midpoint (logged) observed as of the t^{th} transaction, and m_{t^-} the unobservable efficient price. Let LT_{t^-} be the signed volume of pre-workup (or "lit") trading, and (DT_{t^+}) the signed volume of workup (or "dark") trading. Both volume variables are positive if the t^{th} transaction is a buy, and negative if it is a sell.

The basic building blocks of the model are:

$$m_{t^-} = m_{t^- -1} + w_{t^-} \quad (1)$$

$$P_{t^-} = m_{t^-} + cLT_{t^-} \quad (2)$$

$$LT_{t^-} = v_{1,t^-} + \beta_1 v_{1,t^- -1} \quad (3)$$

$$w_{t^-} = u_t^- + \lambda_1 v_{1,t^-} + \lambda_2 v_{2,t^+ -1} \quad (4)$$

$$DT_{t^+} = v_{2,t^+} + \beta_2 v_{2,t^+ -1} + \alpha_1 v_{1,t^-} + \alpha_2 u_t^- \quad (5)$$

where the efficient price m_{t^-} is specified to follow a random walk as in equation (1). w_{t^-} is the efficient price increment and the subscript t^- indicates that the price updating takes place with the execution of the t^{th} market order, but before the workup begins. The observed price P_{t^-}, as expressed in equation 2, consists of the permanent component m_{t^-} as well as a component reflecting trading frictions (cLT_{t^-}). Since workup trades are conducted at the price determined in the pre-workup trading round, P_{t^-} depends contemporaneously on the lit trade flow LT_{t^-} but not on the dark trade flow DT_{t^+}.

To allow for the positive auto-correlation of transaction sign as predicted by theory (for example, Parlour (1998)) and observed in the data, a MA(1) model is specified for the lit trade flow as in equation (3), where v_{1,t^-} is a white noise process and captures the pre-workup trade innovation. Likewise, equation (5) for the dark trade flow DT_{t^+} has an MA(1) error structure with the error term v_{2,t^+}. However, it also includes the contemporaneous effect of the innovation in lit trade flow v_{1,t^-} that precedes and initiates the workup process, as well as public information that arrives at the time of the trade u_{t^-}.

Equation (4) models the efficient price increment w_{t^-} as consisting of both a public information component u_{t^-} that is unrelated to trade and a trade-related private information component. The latter component consists of non-public information inferred from the lit trade flow, as well as the lagged dark trade flow. While workup trades have no immediate price implication as they are executed at an established price, traders can observe the workup trade flows after each transaction and update their belief about the fundamental security value in subsequent transactions. Therefore the dark trading innovation enters the efficient price increment equation with a lag. Finally, the model's innovation terms, namely u_{t^-}, v_{1,t^-} and v_{2,t^+} are assumed to be uncorrelated.

From this point, we simplify the notation by suppressing the plus and minus superscripts of t. With this setup, we can derive a VMA(2) for $Y_t \equiv \begin{bmatrix} LT_t & \triangle P_t & DT_t \end{bmatrix}^T$ with an error vector ϵ_t, where ϵ_t relates to the model's exogenous variables through the following expression: $\epsilon_t = B \begin{bmatrix} v_{1,t} & u_t & v_{2,t} \end{bmatrix}^T$, with:

$$B = \begin{bmatrix} 1 & 0 & 0 \\ \lambda_1 + c & 1 & 0 \\ \alpha_1 & \alpha_2 & 1 \end{bmatrix}. \tag{6}$$

Assuming invertibility condition, a VAR representation (of infinite order) exists for Y_t with the error vector ϵ_t and a covariance matrix $\Omega \equiv \text{Var}(\epsilon_t)$. The matrix B accordingly captures the contemporaneous dynamic structure of the model. It is a lower triangular matrix, reflecting our key assumption with respect to the causal ordering in the model. Specifically, the ordering goes from pre-workup trades to price update and finally to workup trades (which also corresponds to the way we intentionally stack up the vector Y_t). Price revision following the pre-workup trade variable reflects the commonly adopted assumption in the literature that traders watch order flow to update their beliefs about the fundamental value of a security. That the pre-workup trade variable and price revision precede the workup trade variable in the ordering is natural given the way the workup process works: a market order (i.e., pre-workup, or originating, trade) must arrive and execute against standing limit orders before the workup process opens at the established price point.

Formulated this way, the model implies that the price revision incorporates two sources of information: 1) public information unrelated to trades (u_t), and 2) private information inferred from the contemporaneous trade flow innovation ($v_{1,t}$) and the previous workup trade flow innovation ($v_{2,t-1}$). The role of private and public information in the process of price formation in the U.S. Treasury bond market has been well studied in the literature (e.g., Pasquariello and Vega (2007)). Our model goes one step further by delineating the sources of private information and quantifying the informational importance of workup trade activities separately from the information content of initiating a market order. For comparison, we also estimate a standard model of the price impact of trades with only the generic transaction volume, which we refer to as the "bivariate" model (as opposed to our "trivariate" model).

3.2 Permanent Price Impact of Trades

The VAR representation discussed in the previous section can be fit to the data and the permanent price impact of the respective components of order flow can be evaluated. For empirical implementation, we estimate a structural VAR(5) model. Given the assumed ordering discussed earlier, the structural dynamics (i.e., the matrix B as well as the structural variance $\sigma_u^2, \sigma_{v_1}^2$, and $\sigma_{v_2}^2$) can be fully identified.

The long-run cumulative response of price provides a measure of the permanent price impact which is attributable to information and not transitory liquidity effects (see Hasbrouck (1991)). In other words, it corresponds to the increment in the efficient price w_t:

$$\mathbb{E}\left[\triangle P_t + \triangle P_{t+1} + ...|\epsilon_t\right] = \Psi_{\infty,P}\epsilon_t \quad (7)$$

We approximate $\Psi_{\infty,P}$ by computing the cumulative impulse response function (IRF) out to a sufficiently long horizon over which the price response has stabilized and any transitory effects have washed out. As is standard in the literature, we compute the IRF for price from the estimated VAR model by forecasting the system recursively forward to the chosen horizon, assuming that the system is initially at rest, i.e., all variables are set to 0 except for the shocked variable. Inspection of the path of the estimated IRFs indicates that a horizon of 50 transactions provides a reasonable approximation of the permanent price impact $\Psi_{\infty,P}$. The price impact is measured with units in hundredths of a percent of par value (basis points), which is equivalent to cents per \$100 par value. The model is estimated separately for each day in our sample.

Figure 4 plots the average cumulative change in price up to 25 transactions following an initial \$1 billion shock in trade volume initiated from the buy side. The figure shows clearly that the transparent part of order flow has a much greater price impact than the dark part for most securities. The only exception is in the 2-year note, where the impact of the pre-workup and workup trade flows is comparable. The figure also shows that the cumulative price response largely settles by the fifth transaction.

The estimated permanent price impact per \$1 billion shock is reported in Table 3. The table shows the mean and the 95% range of the time series of the daily price impact estimates separately for pre-workup trade flow (under the "Lit Trades" column) and workup trade flow (under the "Dark Trades" column). The mean impact is monotonically increasing in maturity, and this pattern applies to both the pre-workup and workup trade flow. At the shorter end, the 2-year note price increases by merely 3.7 bps if the trading volume during the pre-workup phase increases by \$1 billion. In sharp contrast, the same shock, if it occurs in the 30-year bond, induces a permanent increase of nearly 400 bps, about a hundred times larger. With respect to workup trade flow, the differential in the price impact between the two maturity ends is not as extreme: 51 bps for the 30-year versus 3 bps for the 2-year. In between, the 5- and 10-year notes exhibit a more moderate difference: the price impact of the latter is slightly more than twice that of the former. The ranges of price impact estimates for lit and dark trade flow also generally respect the ordering by maturity just discussed, except for the 30-year bond where a much wider range is observed.

Finally, it is useful to look at the variation over time of the price impact to gain an understanding of how market liquidity has evolved. Figure 5 plots the 20-day moving average of price impact over the sample period. Considering first the price impact of initiating a market order, one can see a significant increase during the crisis period (from August 2007 to June 2009), with the sharpest increases (to about four to eight times larger than the pre-crisis level) occurring in late 2008. This is consistent with the patterns of market depth and bid-ask spreads, other measures of market liquidity, shown in Engle, Fleming, Ghysels, and Nguyen (2012), in suggesting that the market was markedly less liquid during the crisis.

The price impact of workup trades also varies significantly over time, albeit less so than the price impact of pre-workup trades, with a mild increase during the crisis period. There is thus roughly a doubling of price impact from the pre-crisis level to the peak of the crisis for the 5-, 10-, and 30-year securities, versus a four- to six-fold increase for the pre-workup trades. For the 2-year note, there is roughly a quadrupling of price impact at the peak of the crisis for the workup trades, versus a roughly eight-fold increase for the pre-workup trades. The differential response during the crisis means that the 2-year note's price impact estimates for pre-workup and workup trades, which are similar for the pre-crisis period, separate out during the crisis. Taken together, the evidence indicates that initiating a trade produces a greater impact than waiting to trade the same quantity during a workup, and that this gap is more pronounced during times of crisis.

3.3 Information Content of Workup Trades

To evaluate the informational value of workup trades, we follow the information share framework as introduced in Hasbrouck (1991) and applied widely in subsequent studies of price discovery. Conceptually, the information share of a variable measures the extent to which its variation contributes to the variance of the efficient price update w_t. From equation (7), this variance can be approximated by:

$$\tilde{\sigma}_w^2 = \Psi_{h,P} \Omega \Psi_{h,P}^T \tag{8}$$

Given the structure of the system, it is easy to show that the right-hand side of equation (8) is a linear combination of $\sigma_u^2, \sigma_{v_1}^2$, and $\sigma_{v_2}^2$. Each of these terms can then be expressed as a percentage of σ_w^2 and is referred to as the "Hasbrouck information share" of the relevant variable. Specifically, the percentage attributable to σ_u^2 indicates the extent to which public information drives the variation in the efficient price update, whereas those attributable to $\sigma_{v_1}^2$ and $\sigma_{v_2}^2$ quantify the contribution of non-public information revealed through the trade flows during the pre-workup and workup phases respectively. The information share statistics thus allow us to disentangle the information structure and determine the degree of private information being conveyed in workups in comparison to that conveyed through the normal/visible trade flows.

The information share estimates are reported in Table 4. We observe that the informativeness of the lit trade flow is quite consistent across all four securities, ranging on average between 15% and 19%. At the 95% upper bound, this part of order flow explains about 30% or more of the total variation in the efficient price innovations for each of the 2-, 10-, and 30-year securities, and about 26% for the 5-year note.

In contrast, there is a much wider range for the informational value of workup trades across maturities. On the one hand, the dark trade flow of the 2-year note drives about 17% of the variation in the efficient price – slightly higher than the contribution of the lit trade flow. On the other hand, there is almost no private information revealed by the workup trade flow for the 30-year bond (1%). Even the 95% upper bound for the bond is only about 5%. In between, the 5- and 10-year notes are quite similar in terms of workup trade informativeness, with average contributions of 7 and 8% respectively, and corresponding 95% upper bounds of 18% and 21%.

Despite the importance of trade flow, the table also shows that public information is nonetheless the main driver of the variation in the efficient price. For the 5- and 10-year notes, the average contribution of public information to the price discovery process is between 73-77%, with a 95% range of roughly 60-90%. The 30-year bond has a slightly higher public information share, with a mean of 82% and a 95% range between 69% and 94%. The 2-year note shows a slightly lower public information share, averaging 67% and ranging between 42% and 88%. That is, trade flow is most informative at the short maturity end and least informative at the long maturity end. Moreover, the breakdown between lit and dark trades shows that this overall differential between public information and trade-related information is explained mainly by the differential in the informativeness of workups.

The time series of the information shares, presented in Figure 6, show that the informativeness of the lit trade flow appears rather stable over time, with a slight increase toward the end of the sample period. On the other hand, the informational role of the dark trade flow changes more appreciably over time, most notably among the notes. The information share of workup trades trended down through much of 2007 and 2008, before rebounding in 2009. The information share of workup trades for the 2-year note settled at a new higher level after 2009, whereas the share remained similar or lower than pre-crisis levels for the 5- and 10-year notes, respectively.

3.4 Information Structure on Special Days

We now analyze the information structure on days of special interest. We specifically look at days with important announcements, days when the market is highly volatile, and days when the market experiences extreme buying pressure – an indicator of a possible flight-to-safety. Table 5 documents this analysis. Under each security, there are three columns: Lit Trades, Dark Trades and Public Information. Different from Table 4 where we report the raw information shares of lit and dark trades, in this table, the respective shares are standardized by the total trade-related information share, i.e., these two columns add up to 100%. This makes it easier to see the relative informational importance of lit versus dark trade flow. The private versus public information split can be gauged by examining the public information share reported in the third column for each security.

3.4.1 Announcement Days

In Table 5, Panel A, we compare non-announcement days to days with announcements of: 1) FOMC rate decisions, 2) important macroeconomic releases, and 3) auction results.[14] These announcements have been shown to be important to Treasury price formation (see Fleming and Remolona (1997), Balduzzi, Elton, and Green (2001), Green (2004), Pasquariello and Vega (2007) and references therein). For each of these announcement types, we compare the relative informativeness of the lit and dark trade flow on announcement days with that estimated on days when none of these three announcement types occurs.

Interestingly, there is no major change in the private information structure on announcement days, as compared to non-announcement days. That is, the mix of information content of lit and dark trade flow remains quite similar across different announcement types (including no announcement). However, the trade flow collectively has relatively less information value on FOMC and macroeconomic announcement days. This result is intuitive, because there is a greater amount of public information arriving on these announcement days which can move prices without requiring trades, as shown in Fleming and Remolona (1999) and other studies.

[14]See Appendix A for the list of announcements considered.

3.4.2 Volatile Days

Table 5, Panel B shows a comparison of the information structure on highly volatile days against days with low volatility (based on the 95th and 5th percentiles of the volatility distribution). We first focus on the private information mix. Consistently across all four securities, the pre-workup trade flow – the lit part – is relatively more informative on high volatility days. It is helpful to tie this result to an earlier stylized fact that workups are used more on volatile days, and, particularly for the notes, more often expand the quoted depth. We interpret these results collectively as indicating that: 1) information is short-lived in volatile times, necessitating fast execution and 2) the increased incidence of quoted depth expansion reflects how liquidity providers (not necessarily informed) use the workup option to guard against adverse execution of their orders.

It is also interesting to see that public information takes on a greater role in price discovery when the market is highly volatile, as compared to when the market is tranquil. That trades are relatively less informational when price is highly volatile is to be expected, because the variance of the efficient price update is a linear combination of the variances of return and the two order flow variables. When price fluctuates greatly, this variability dominates the variance of the efficient price update, leaving a lesser role for trade-related information in the price formation process. An intuitive way to think about this result is that noisier public information makes it harder for market participants to interpret trade flow patterns and discern value-relevant information.

3.4.3 Days with Extreme Net Order Flow

In Table 5, Panel C, we compare the information structure on days with high net inflows and high net outflows (based on the 95th and 5th percentiles of the distribution of net order flow). Net order flow, if positive, suggests a possible flight-to-safety into Treasury securities (see Beber, Brandt, and Kavajecz (2009)), whereas strongly negative net order flow suggests a flight out of Treasury securities. The results show that the 2- and 10-year notes do not exhibit a statistically significant change in the information structure between flights into and out of Treasuries. In contrast, the lit order flow of the 5- and 30-year securities becomes relatively more informative on days with high flows into the market, compared to flows out of the market. However, the shift is fairly small in magnitude. Furthermore, most securities show a similar public information share between high inflow and high outflow days. Overall, the nature of the flows in the market does not seem to alter substantially the information structure and workup characteristics.

3.5 Comparison with Standard Model of Price Impact of Trades

Our analysis in the previous section illustrates that delineating the trade flow into the pre-workup and workup components permits a more complete understanding of how the different layers of the trading process convey non-public information and affect price dynamics. One of the key findings is that trade flow is not homogeneous. A $1 million trade initiated in the pre-workup stage generally results in a greater price impact and carries more information than when the same trade occurs in the workup stage.

As a result, if we model only the trade volume variable without considering its respective components, we may underestimate the price impact of a market order, since the lower impact of the workup component pulls down the estimate for the whole transaction size. In addition, omitting the possible endogenous interaction of workup and pre-workup activity might underestimate the overall informativeness of order flow. To formally see this, we estimate a bivariate VAR(5) of trade flow and return, and compute the permanent price impact as well as the information share of transaction volume. The comparison to the trivariate results is provided in Table 6.

Panel A illustrates that for the 5-, 10- and 30-year securities the price impact of a lumped-together (or "generic") trade estimated from the bivariate model is much smaller than the price impact of a market order of the same size estimated from the trivariate model (about half the magnitude). At the same time, Panel B shows that the price impact of a generic trade is higher than the price impact of a trade occurring during a workup.

For the 2-year note, the estimated price impact of a generic trade is not only lower than the estimated price impact of a market order (Panel A), but also lower than the price impact of a workup trade (Panel B). As discussed earlier, workup activity in the 2-year note is generally as informative as pre-workup trading activity. Failure of the bivariate model to capture the endogenous dynamics between workups and trade initiation featured in our trivariate model results in a lower price impact estimate than that of workups for the 2-year note.

In addition, as shown in Panel C, the bivariate model attributes less information value to order flow. Our tests of the hypothesis that the information share of trades in the model of segmented order flow is not higher than that implied by the bivariate model are rejected for three of the four securities considered. This is because the bivariate model does not capture and attribute adequately the different contributions and variations in the respective components of the overall order flow. More importantly, as discussed above, the dynamic interaction between pre-workup and workup order flow is absent in the bivariate model, implying a lower information role of order flow than is the case when this dynamic interaction is taken into account.

Economically, it is important to recognize that the workup option is an integral part of the trading process in the Treasury interdealer market. It is undoubtedly factored into the trading decisions of dealers, since they can choose to trade immediately by submitting a market order, or wait to trade in a workup. Factors such as liquidity need, degree of impatience and/or possession of short- versus long-lived information might contribute to the segmentation of order flow, as dealers balance faster execution with higher price impact. Treating this market as one where such a workup option is not available and trade flow is homogeneous may give rise to a less than accurate characterization of the trading process and how trading affects price dynamics.

3.6 Is Direction of Workup Expansion Informationally Relevant?

As discussed earlier, the workup protocol on the BrokerTec electronic platform differs from the voice-assisted protocol described in Boni and Leach (2004) in that workup volume can originate from either side, as opposed to just expanding the limit order book. The analysis performed up to this point has considered all workup volume to be equal, but additional insight may be gained by examining whether the direction of volume expansion during a workup matters to price discovery. Our results show that this is indeed informationally relevant.

To proceed, we estimate an expanded VAR model in which the workup trade flow (DT) is replaced by three workup trade flow types (DT_1, DT_2, and DT_3). These are workups that expand volume on: 1) the aggressive side (DT_1), 2) both sides (DT_2), and 3) the passive side (DT_3).[15] The vector of endogenous variables is now $Y_t \equiv \begin{bmatrix} LT_t & \triangle P_t & DT_{1,t} & DT_{2,t} & DT_{3,t} \end{bmatrix}^T$. To check whether the relative importance of each of these workup trade flow types is sensitive to the VAR variable ordering, we also report the results based on an alternative ordering in which the different

[15] See subsection 2.4.4 for a detailed description of this classification.

workup trade flow categories are reversed, i.e., $Y_t \equiv \begin{bmatrix} LT_t & \triangle P_t & DT_{3,t} & DT_{2,t} & DT_{1,t} \end{bmatrix}^T$. From the estimated VAR, we compute the information share for each of the variables in the system as described earlier, and report them in Table 7. For brevity, the information shares of lit trades and public information are not shown as they are quite similar to the previously reported results.

The results indicate that workup volume coming from the aggressive side contributes significantly more to price discovery. For example, the information share of workups that expand the aggressive side averages 13% for the 2-year note, compared with the 6% information share of workups that expand both sides and the 1% information share of workups that expand the passive side. Interestingly, this pattern holds even for the 30-year bond, where workups mainly expand the passive side. A comparison of the two orderings shows that the results are not ordering sensitive.

To see whether the information contribution of each type of workup order flow is commensurate with its share of volume (shown in Figure 3), we rescale the three information shares so that they add up to 100%. The rescaled numbers indicate the relative contribution of each workup type to the total informativeness of workup order flow. We use the mean information shares based on the first variable ordering for this calculation, but the result is similar for the other ordering. The relative information contribution of aggressive workups is 63.9%, 64.1%, 64.1%, and 64.2% respectively for the 2-, 5-, 10- and 30-year securities. These percentages are consistently higher than the volume share of aggressive workups, which are 53%, 38%, 29% and 22%. That is, aggressive workups are disproportionately more informative than the other two workup types.

4 Determinants of Workup Trades

As the previous section shows, trading activity that takes place during the workup stage has a non-trivial role in the price discovery process. Additionally, workups take place in more than half of transactions and account for a large share of volume transacted in this market. Collectively, these findings provide a motivation for our subsequent analysis exploring the determinants of the workup option and the extent of volume transacted during this phase. Being able to predict the likelihood and extent of a workup upon the arrival of the next market order, based on prevailing market conditions, can be valuable to market participants in making trading decisions.

In order to identify workup determinants, it is important to understand workup benefits and costs. The most natural cost of waiting to transact in a workup is the risk of non-execution and perhaps the loss of private information advantage, since counter trading interest may not exist in a workup. Therefore, variables that correlate with non-execution risk or the perishability of private information are expected to be negatively associated with workup usage and workup volume.

On the other hand, the obvious benefit of the workup protocol is that traders have more flexibility with what to do with their trading intention, including not doing anything at all if the market moves unfavorably. This provides an important advantage over iceberg orders, since the hidden part of an iceberg order may get executed adversely before the trader has a chance to modify or cancel. Furthermore, the ability to expand volume during workups can be valuable to those traders with a large trading interest. By submitting an initial small sized order, those traders can avoid causing adverse price impact that could have resulted had they submitted the full-sized large order altogether.

The use of workups therefore reflects a trade-off among non-execution risk, increased control over one's trading activities, and the ability to avoid adverse price impact. We thus model the probability of workup (i.e., whether or not a transaction has a workup), as well as the magnitude of the workup volume, with the following explanatory variables capturing this trade-off:

- *DepthSame*: prevailing inside depth on the same side of the transaction (logged).
- *DepthOpp*: prevailing inside depth on the opposite side of the transaction (logged).
- *PretradeSpr*: prevailing relative spread in basis points $\left(10,000\frac{P_A-P_B}{(P_A+P_B)/2}\right)$.
- *MoSize*: pre-workup volume of the transaction (i.e., the volume transacted before the workup start) (logged).
- *HdRevealed*: whether trading activities during the pre-workup stage have revealed any iceberg orders.
- *AveDurLast5*: average transaction duration (in seconds) in the last five minute interval (logged).
- *Vola5Min*: volatility as measured by the high low range of the logged mid-quote over the last five minute interval, capturing the level of volatility immediately before the transaction.

- *PctWkup5Min*: percentage of transactions with a workup in the last five minute interval, to control for the possible liquidity externality of workup activities as predicted by Buti, Rindi, and Werner (2011a)'s model.
- *PctWkupV5Min*: percentage of volume expanded during workups (conditional on workup usage) in the last five minute interval. This is another control for the liquidity externality.
- *Tokyo trading hour dummy*: equals 1 if the transaction starts during the period from 18:30 EST (or 19:30 EDT) the previous day to 3:00 ET.
- *London trading hour dummy*: equals 1 if the transaction starts during the period from 3:00 ET to 7:30 ET.

We employ a logistic regression model for the probability of workup, in which the dependent variable equals 1 for those transactions with workup, and 0 otherwise. For the extent of volume expansion during a workup, we estimate a Tobit model in which the dependent variable is the workup volume, and those transactions with no workup are censored at zero. The model estimates are presented in Table 8. Given the large number of observations, most of the coefficient estimates are significant at the 5% level. Only those coefficients that are not significant are marked with an asterisk. We discuss each determinant below.

First, the prevailing depth on the same side is positively related with both the probability of workup and the magnitude of workup volume. This supports the argument that a higher level of depth, indicative of longer time to execution for the marginal limit order, might encourage traders with trading interest on the same side to opt for the immediate execution opportunity offered by the workup. This finding is enhanced by the negative relationship between prevailing spread and the likelihood of workup.[16] A tighter spread (the spread is often 1 tick in this market) makes it harder to post limit orders inside the spread, while simultaneously reducing the cost to trade at the workup price (i.e., the forgone spread). Thus, the choice of immediate execution becomes more attractive, despite it being at a worse price than that of a limit order price. Both of these findings provide empirical support for Buti, Rindi, and Werner (2011a)'s model of dark pool trading strategies in limit order markets.

[16] Note that once the workup choice is made, the effect of prevailing spread on the extent of volume expansion during the workup is mixed: negative for the 2- and 10-year securities, but positive for the 5- and 30-year securities.

Our finding concerning the effect of depth on the opposite side provides some insight into what matters more to traders when the market is shallow on the opposite side. Theoretically, the effect of opposite side depth on the likelihood and extent of a workup can go either way. On the one hand, the model by Buti, Rindi, and Werner (2011a) shows that lower depth on the opposite side to absorb incoming orders can result in more adverse price impact for incoming trades. If so, the workup protocol can be valuable as it gives traders an option to start with a smaller sized order and expand the size in a workup without bearing significant market impact. On the other hand, lower depth on the opposite side may be a sign that trading interest on that side is lacking. This can reduce the execution probability of trades in a workup, resulting in a lower likelihood of successful matching during the workup window. Even if a workup does occur, the workup quantity is likely to be lower.

Our empirical evidence of a positive relationship for most securities supports the latter argument; that is, non-execution risk appears to be a more important consideration than the adverse price impact concern. The only exception is the 2-year note, for which we observe a negative effect of opposite side depth on the likelihood of a workup. Recall that the transaction size in the 2-year note is often much larger than that for other securities. Accordingly, the adverse price impact associated with the lack of opposite standing depth might become a more important concern, thereby encouraging greater usage of workups. As for workup quantity, the effect of opposite side depth is also positive for all securities, providing additional support for the non-execution risk hypothesis.

Next, the initial size of a transaction is positively associated with the likelihood of workup (as shown by the positive coefficients for pre-workup volume across securities, except for the 30-year bond). This provides direct empirical support of Harris (1997)'s argument that there might be inactive traders in the market who only take action based on the actions of others. A larger volume transacted during the pre-workup phase is more likely to ignite interest from otherwise inactive traders. Another possible explanation is that large initial volume is perceived by the market to be associated with large liquidity demand. This may induce the expansion of the quoted depth during the workup beyond the level observed just before the trade – an idea that finds empirical support in Boni and Leach (2004). Interestingly, once a workup is taking place, the additional volume transacted may increase or decrease with the pre-workup volume depending on the security. For example, it is positive for the 2- and 30-year securities but negative for the 5- and 10-year notes.

Another aspect of pre-workup trading – the revelation of hidden depth – can also predict higher workup usage and volume expansion. The revelation informs market participants that there is a hidden liquidity pool in addition to the initially observed depth and that workup trades have a greater chance of being filled/absorbed.

We further find that price volatility, measured over the 5-minute time window leading to each transaction, is positively related with workup activities. This is consistent with Boni and Leach (2004)'s finding using GovPX data under a protocol in which workups expand the limit order book only. Intuitively, when the market is volatile, the risk of adverse execution of limit orders increases, thereby motivating a greater reliance on workups because the protocol allows traders greater control over when and how much to trade, or even not to trade at all.

Moreover, since the workup protocol can be likened to a crossing network, we can also borrow theoretical insights from that literature for a better understanding of our empirical volatility finding. Ye (2012) suggests a linkage between security value uncertainty and the choice of trading in the crossing network as opposed to the transparent exchange. Specifically, uncertainty increases both the price impact of trades on the exchange and the non-execution probability in the crossing network, but the net effect is that the crossing network is comparatively more beneficial for the informed traders. As a result, Ye predicts that crossing network usage should increase in value uncertainty. Our finding concerning the effect of volatility is generally in line with this prediction, as well as empirical evidence in Ready (2012) for a cross section of the 500 largest NASDAQ stocks from 2005 to 2007.

Our result also shows that the speed of trading in the market significantly increases the likelihood of a workup, as well as the magnitude of worked-up volume. In light of Easley and O'Hara (1992) and Dufour and Engle (2000), high trading intensity is likely reflective of information arrival, and thus, inactive trading interest can be activated and revealed in a workup following the lead of market order traders. Furthermore, the positive coefficients for the prevailing level of workup activity support Buti, Rindi, and Werner (2011a)'s argument that dark pool liquidity begets dark pool liquidity, as a higher level of workup activity signals an increased chance of finding counter-party trading interest and successful execution of workup orders.

Finally, the probability of workup and extent of worked up volume are both significantly lower outside New York trading hours, even after having controlled for the level of trading activity through the previously discussed covariates. This seems to be consistent with the hypothesis that workups are used less in the overnight hours when there are fewer traders in the market. There is simply a lower chance of meeting with a counter-party in a workup, or being able to ignite inactive trading interest, when there are not many traders at their desks.

5 Conclusion

This paper studies the workup protocol, a distinctive and frequently used trading feature in the U.S. Treasury securities market. Given its importance in discovering a large portion of market liquidity, we examine its role in the price formation process, and distinguish it from the information value of non-workup trades that initiate workups. We find that workup trade flow generally contains less information than its transparent counterpart, but that its role is not trivial. In addition, it is the aggressive side workups that account for most of the information value of workup trade flow. Workups that expand the limit order book as described in Boni and Leach (2004) are far less informative.

Furthermore, we find that workups occur more frequently around volatile times, when the incidence of workups expanding the pre-trade limit order book also increases for all three notes, suggesting that the workup protocol is helpful to limit order traders in managing their trading interest. Additionally, workups are more likely when the market is more liquid (e.g., greater market depth and tighter bid-ask spreads) or trading more active. Interestingly, lit order flow becomes more informationally relevant on highly volatile days, supporting the belief that traders with better information are more likely to initiate trades and exploit their information before adverse price movements can render the information less valuable. Taken together, the evidence seems to suggest that workups are used more as a channel for liquidity providers to guard against adverse price movements, than as a channel to hide private information.

Our findings provide important implications for research into the price discovery of U.S. Treasury securities. Consistent with theory, we document that the different layers of order flow have different information content. Intuitively, given the option of trading in a workup, a trader who chooses to initiate a trade (as opposed to wait for a workup) conveys a stronger signal to the market than otherwise would be the case in a hypothetical market setup where such a workup option does not exist. Therefore, the act of initiating a trade should contribute more to information discovery than the act of trading in a workup. We show that, without considering this segmentation, the price impact so estimated can underestimate the impact of initiating a trade and the share of non-public information flow.

Beyond the literature on price discovery in financial markets, our research adds to two important areas of research, namely dark pool trading and security market design. The workup protocol in essence is a dark pool mechanism and provides a valuable opportunity for examining how such a mechanism operates in a fixed income market setting. We show that in the market for U.S. Treasury securities, dark pool trades are only mildly informative and that they tend to occur more often at more volatile times, highlighting the benefit of this mechanism in protecting traders against large price swings. While equity dark pools have recently come into the spotlight for the potential of compromising market quality and fairness, our evidence indicates that this is not a major concern for this fixed income market, one that is populated mostly by sophisticated market participants (i.e., government securities dealers).

With respect to security market design, the workup protocol presents an interesting case study of a continuous limit order market combined with periodic call auctions. This is a timely contribution to the current discussion on the market design response to the trend in high frequency trading. With increasing high frequency trading activity across markets, continuous limit order market design has shown certain limitations (e.g., encouraging an arms race in trading technology). Naturally, these limitations invite further research into alternative market design features and necessitate an understanding of possible implications of such features. In this direction, our paper readily offers empirical implications on trading patterns, exposure choice and price discovery in a continuous limit order market enhanced with periodic auctions.

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Table 1: Summary Statistics of Trading and Workup Activities

	2-Year	5-Year	10-Year	30-Year
PANEL A: DAY-LEVEL STATISTICS				
Volume ($B)	33.5	34.0	29.3	4.7
Pre-workup %	51.8	43.6	45.5	57.3
Workup %	48.2	56.4	54.5	42.7
Number of Transactions	1,224	2,679	2,642	1,464
% with Workup	49.0	56.2	55.2	39.1
% with Iceberg Order Match	4.2	4.3	4.4	3.9
% Executed at Multiple Prices	0.0	0.2	0.2	0.5
PANEL B: TRANSACTION-LEVEL STATISTICS (WITH WORKUP)				
Transaction Size ($M)	41.8	18.6	16.4	5.4
Pre-workup	15.6	6.0	5.5	1.9
Workup	26.2	12.7	10.9	3.5
Number of Trades	9.9	8.7	8.6	3.9
Pre-workup	3.2	2.9	3.0	1.4
Workup	6.7	5.8	5.6	2.5
PANEL C: TRANSACTION-LEVEL STATISTICS (WITHOUT WORKUP)				
Transaction Size ($M)	11.9	4.6	4.2	1.7
Number of Trades	2.4	2.1	2.2	1.3
PANEL D: SAMPLE SIZE				
Number of Transactions	1,836,812	4,017,905	3,946,216	2,197,471
Number of Trading Days	1,501	1,501	1,494	1,501

This table provides summary statistics of trading activity in the on-the-run 2-, 5-, 10-, and 30-year Treasury securities on the BrokerTec platform. The sample period is 2006-2011. A transaction refers to a complete sequence of order executions that starts with the arrival of a market order and ends when the workup initiated by the original market order completes. A trade refers to a single paired order matching. There is no data available for the 10-year note on seven days during the sample period (August 3-7, 10-11, 2009). Numbers reported in Panel A are daily averages. Numbers in Panels B and C are averages across all transactions with and without workups respectively.

Table 2: Correlations of Workup and Order Flow Variables

	2-Year	5-Year	10-Year	30-Year
Daily Signed Order Imbalance & Workup Usage	0.048	0.169	0.043	0.043
Daily Absolute Order Imbalance & Workup Usage	-0.297	-0.266	-0.206	-0.081
Daily Volatility & Workup Usage	0.541	0.380	0.540	0.256
Workup Autocorrelation	0.110	0.084	0.089	0.063
Workup Volume Autocorrelation	0.098	0.120	0.136	0.114

This table shows correlations of workup and trading variables for the on-the-run 2-, 5-, 10-, and 30-year Treasury securities on the BrokerTec platform. The sample period is 2006-2011. A transaction refers to a complete sequence of order executions that starts with the arrival of a market order and ends when the workup initiated by the original market order completes. Daily signed order imbalance is buy volume minus sell volume, standardized by the day's total trading volume. Daily absolute order imbalance is the absolute order imbalance standardized by the day's total trading volume. Daily volatility is the average five-minute realized volatility of the bid-ask midpoint (logged) for each day. Workup usage is the percentage of transactions with workups for each day. The workup and workup volume autocorrelation coefficients are computed based on transaction-level data.

Table 3: Permanent Price Impact of Segmented Order Flow

		Lit Trades	Dark Trades
	Mean	3.70	3.19
2-Year	95% Range Lower Bound	0.76	0.88
	95% Range Upper Bound	13.59	8.57
	Mean	21.88	7.54
5-Year	95% Range Lower Bound	5.23	2.59
	95% Range Upper Bound	59.42	15.44
	Mean	48.16	18.04
10-Year	95% Range Lower Bound	11.02	6.24
	95% Range Upper Bound	129.36	34.00
	Mean	397.97	50.60
30-Year	95% Range Lower Bound	113.59	-61.24
	95% Range Upper Bound	938.46	203.19

This table reports the permanent price impact (in basis points per $1 billion buyer-initiated volume) of pre-workup trades ("Lit Trades") versus workup trades ("Dark Trades"). The estimates derive from a VAR(5) model of pre-workup trade flow, return and workup trade flow. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006-2011. Observations outside the [7:00-17:30] time window are excluded. The model is estimated separately for each day. The mean and 95% range are computed from the time series of daily price impact estimates.

Table 4: Share of Trade and Non-Trade Related Information

		Trade Related Information		Public
		Lit Trades	Dark Trades	Information
	Mean	15.23	17.48	67.28
2-Year	95% Range Lower Bound	3.52	3.01	41.72
	95% Range Upper Bound	30.67	38.67	87.73
	Mean	16.09	6.72	77.19
5-Year	95% Range Lower Bound	6.07	0.54	63.19
	95% Range Upper Bound	26.35	17.82	91.08
	Mean	18.52	8.21	73.28
10-Year	95% Range Lower Bound	7.83	0.67	59.11
	95% Range Upper Bound	30.10	21.19	86.53
	Mean	16.66	1.05	82.29
30-Year	95% Range Lower Bound	5.66	0.00	68.69
	95% Range Upper Bound	29.95	5.13	93.73

This table reports the information share (%) of pre-workup trades ("Lit Trades"), workup trades ("Dark Trades"), and non-trade-related information ("Public Information"). The estimates derive from a VAR(5) model of pre-workup trade flow, return and workup trade flow. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006-2011. Observations outside the [7:00-17:30] time window are excluded. The model is estimated separately for each day. The mean and 95% range are computed from the time series of daily information share estimates.

Table 5: Information Structure on Days with Announcements and Extreme Market Movements

	2-Year			5-Year			10-Year			30-Year		
	Lit Trades	Dark Trades	Public Info	Lit Trades	Dark Trades	Public Info	Lit Trades	Dark Trades	Public Info	Lit Trades	Dark Trades	Public Info
PANEL A: ANNOUNCEMENT VERSUS NON-ANNOUNCEMENT DAYS												
FOMC Announcements	47.66	52.34	72.58*	72.51	27.49	84.19*	71.27	28.73	78.94*	94.38	5.62	86.34*
Macro Announcements	47.82	52.18	67.93*	72.22	27.78	78.30*	70.84	29.16	74.15*	93.60	6.40	83.05*
Auction Days	47.03	52.97	66.89	70.79	29.21	77.76*	69.95	30.05	73.01	95.38	4.62	82.36
Non-Announcement Days	49.30	50.70	66.18	71.56	28.44	75.29	69.72	30.28	71.83	93.84	6.16	81.02
PANEL B: DAYS WITH EXTREME VOLATILITY												
High Volatility Days	62.30*	37.70*	78.94*	83.51*	16.49*	84.28*	86.18*	13.82*	78.10*	95.70*	4.30*	83.66
Low Volatility Days	48.47	51.53	67.48	72.66	27.34	77.40	71.25	28.75	73.56	93.97	6.03	82.45
PANEL C: DAYS WITH EXTREME ORDER IMBALANCES												
High Inflow Days	50.11	49.89	66.15	76.64*	23.36*	76.53	68.72	31.28	73.03	95.69*	4.31*	84.01*
High Outflow Days	48.30	51.70	67.21	72.09	27.91	77.14	70.67	29.33	73.28	93.69	6.31	82.29

This table reports the relative informativeness of pre-workup order flow ("Lit Trades") versus workup order flow ("Dark Trades") and the share of public information ("Public Info") on: A) days with announcements versus non-announcement days; B) high volatility days versus low volatility days; and C) high inflow days versus high outflow days. The thresholds for high and low volatility, and similarly for high inflow and high outflow, are the 95th and 5th percentiles of the distributions for volatility and net order flow (Buy Volume minus Sell Volume) respectively. The relative informativeness of each component of the order flow is measured by its information share as a percentage of the total trade-related information share. The public information share is 100% minus the total trade-related information share. The information shares are computed from a VAR(5) model of pre-workup trade flow, return and workup trade flow. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006-2011. Observations outside the [7:00-17:30] time window are excluded. An asterisk (*) indicates significantly different informativeness at the 5% level.

Table 6: Informational Content of Segmented versus Generic Order Flow

	2-Year	5-Year	10-Year	30-Year
PANEL A: PRICE IMPACT OF $1 BILLION PRE-WORKUP VOLUME				
Model with Segmented Trade Flow	3.70	21.88	48.16	397.97
Model with Generic Trade Flow	2.74	11.34	25.94	181.00
p-value of paired sample t-test (right tail)	<0.001	<0.001	<0.001	<0.001
PANEL B: PRICE IMPACT OF $1 BILLION WORKUP VOLUME				
Model with Segmented Trade Flow	3.19	7.54	18.04	50.60
Model with Generic Trade Flow	2.74	11.34	25.94	181.00
p-value of paired sample t-test (left tail)	1.000	<0.001	<0.001	<0.001
PANEL C: INFORMATION SHARE OF TRADES				
Model with Segmented Trade Flow**	32.72%	22.81%	26.72%	17.71%
Model with Generic Trade Flow	26.64%	22.76%	26.39%	14.45%
p-value of paired sample t-test (right tail)	<0.001	0.201	<0.001	<0.001

This table compares the price impact and informational content of order flow estimated by our trivariate VAR model, which considers separately the pre-workup and workup order flow, with those estimated by a standard bivariate VAR model, which considers the generic order flow without segmentation. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006-2011. ** This is the combined information share of pre-workup and workup trades.

Table 7: Information Share of Workup Trades by How Workup Volume Arises

		Ordering 1			Ordering 2		
		Mean	95% LB	95% UB	Mean	95% LB	95% UB
2-Year	Aggressive	12.96	2.18	31.18	13.47	2.25	31.97
	Both	6.20	0.52	16.31	5.88	0.39	15.84
	Passive	1.13	0.00	5.96	0.95	0.00	4.98
5-Year	Aggressive	6.55	1.29	14.41	6.81	1.35	14.87
	Both	3.09	0.16	8.72	2.99	0.13	8.68
	Passive	0.58	0.00	3.05	0.43	0.00	2.61
10-Year	Aggressive	7.72	1.59	16.30	8.05	1.66	16.92
	Both	3.73	0.23	10.47	3.56	0.21	10.18
	Passive	0.59	0.00	3.10	0.42	0.00	2.40
30-Year	Aggressive	1.97	0.01	7.10	2.00	0.01	7.13
	Both	0.67	0.00	3.19	0.64	0.00	3.13
	Passive	0.43	0.00	2.42	0.42	0.00	2.42

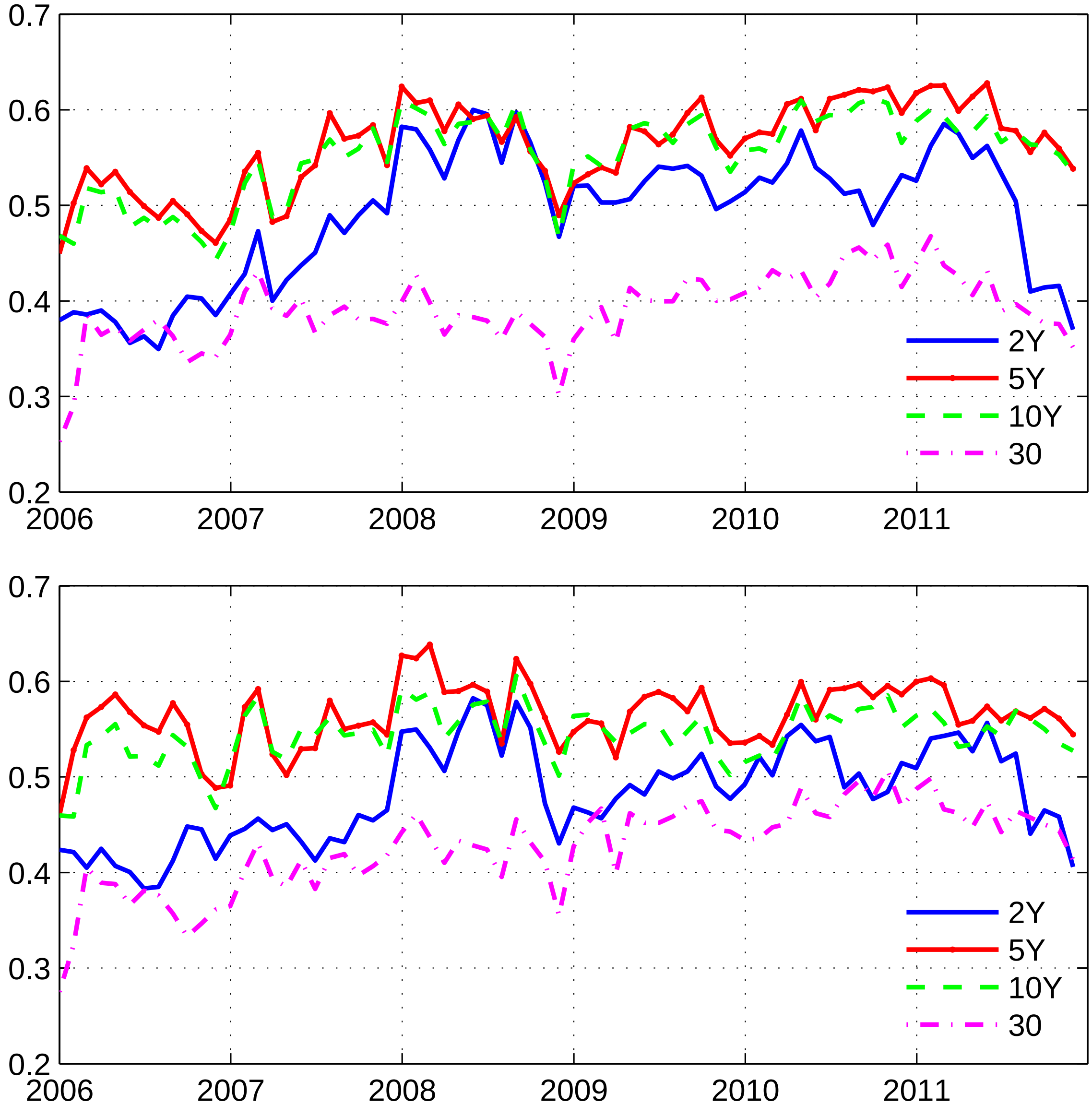
This table reports the % information share of workups classified by how workups expand volume: 1) the aggressive side only, 2) both sides, and 3) the passive side. The estimates derive from a VAR(5) model of pre-workup trade flow, return and three categories of workup trade flow. For brevity, information shares of pre-workup trades and public information flow are not reported. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006-2011. Observations outside the [7:00-17:30] time window are excluded. Ordering 1 columns show the information share based on a variable ordering of Aggressive, Both, and Passive. Ordering 2 columns show the information share based on a variable ordering of Passive, Both, and Aggressive.

Table 8: Determinants of Workups

	2-Year		5-Year		10-Year		30-Year	
	Probability	Quantity	Probability	Quantity	Probability	Quantity	Probability	Quantity
Intercept	-0.037	0.650	-0.031	0.556	0.104	0.556	-0.413	0.670
Pretrade Depth – Same Side	0.131	0.175	0.145	0.164	0.147	0.167	0.049	0.065
Pretrade Depth – Opposite Side	-0.101	0.277	0.081	0.357	0.046	0.365	0.522	0.219
Pretrade Spread	-0.217	-0.067	-0.240	0.008	-0.172	-0.008	-0.009	0.010
Pre-workup Volume (logged)	0.095	0.079	0.081	-0.009	0.087	-0.035	-0.193	0.019
Hidden Depth Revealed	0.156	0.303	0.419	0.414	0.338	0.374	0.992	0.323
Volatility Last5Mins	0.084	0.066	0.042	0.024	0.030	0.013	0.007	0.002
Ave Duration Last5Mins (logged)	-0.174	-0.082	-0.264	-0.094	-0.265	-0.109	-0.207	-0.067
Workup Probability Last5Mins	0.496	0.052	0.641	0.161	0.586	0.162	0.406	0.163
Workup Volume Share Last5Mins	0.176	0.023	0.066	0.016	0.115	0.007 *	0.115	-0.013
Tokyo Trading Hour Dummy	-0.369	-0.131	-0.185	-0.225	-0.308	-0.193	-0.502	-0.119
London Trading Hour Dummy	-0.278	-0.205	-0.134	-0.221	-0.168	-0.237	-0.191	-0.103
Max-rescaled R-squared	0.063		0.076		0.083		0.079	

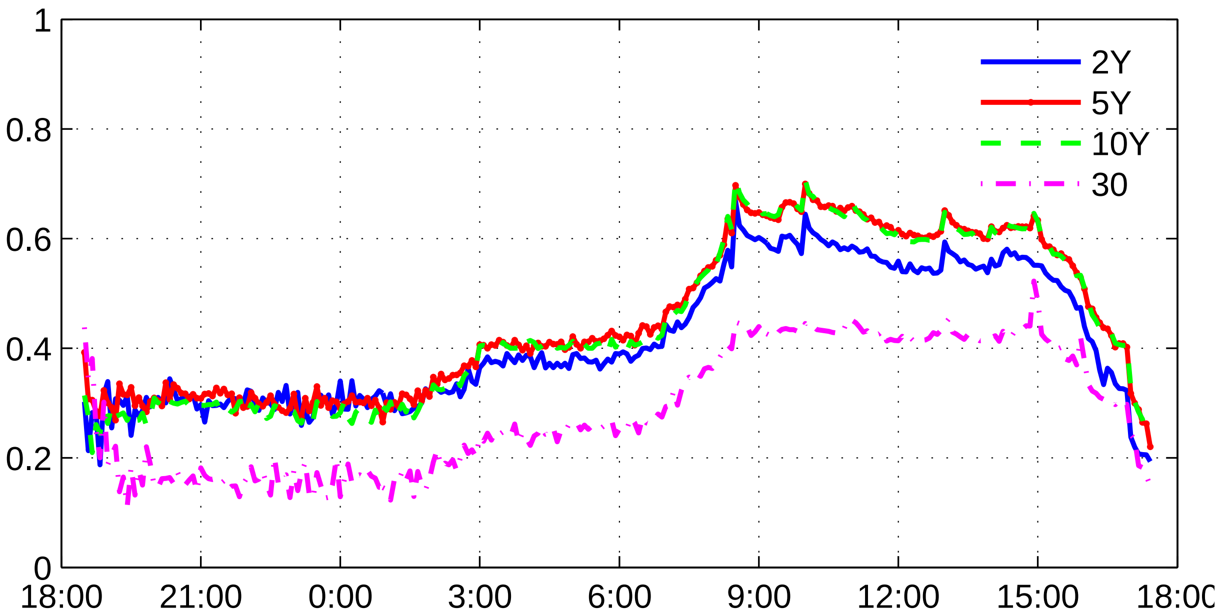
This table reports results of a logistic regression for whether or not a transaction has a workup (under columns titled "Probability"), and a Tobit model for the dollar volume transacted during the workup phase (under columns titled "Quantity"). The models are estimated using BrokerTec data for on-the-run 2-, 5-, 10-, and 30-year Treasury securities over the period 2006-2011. Tokyo trading hour dummy is equal to 1 for the period from 18:30 EST (or 19:30 EDT) the previous day to 3:00 ET. London trading hour dummy is equal to 1 for the period from 3:00 ET to 7:30 ET. Note: an asterisk (*) indicates *in*significance at the 5% level.

Figure 1: Workup Activity over Time



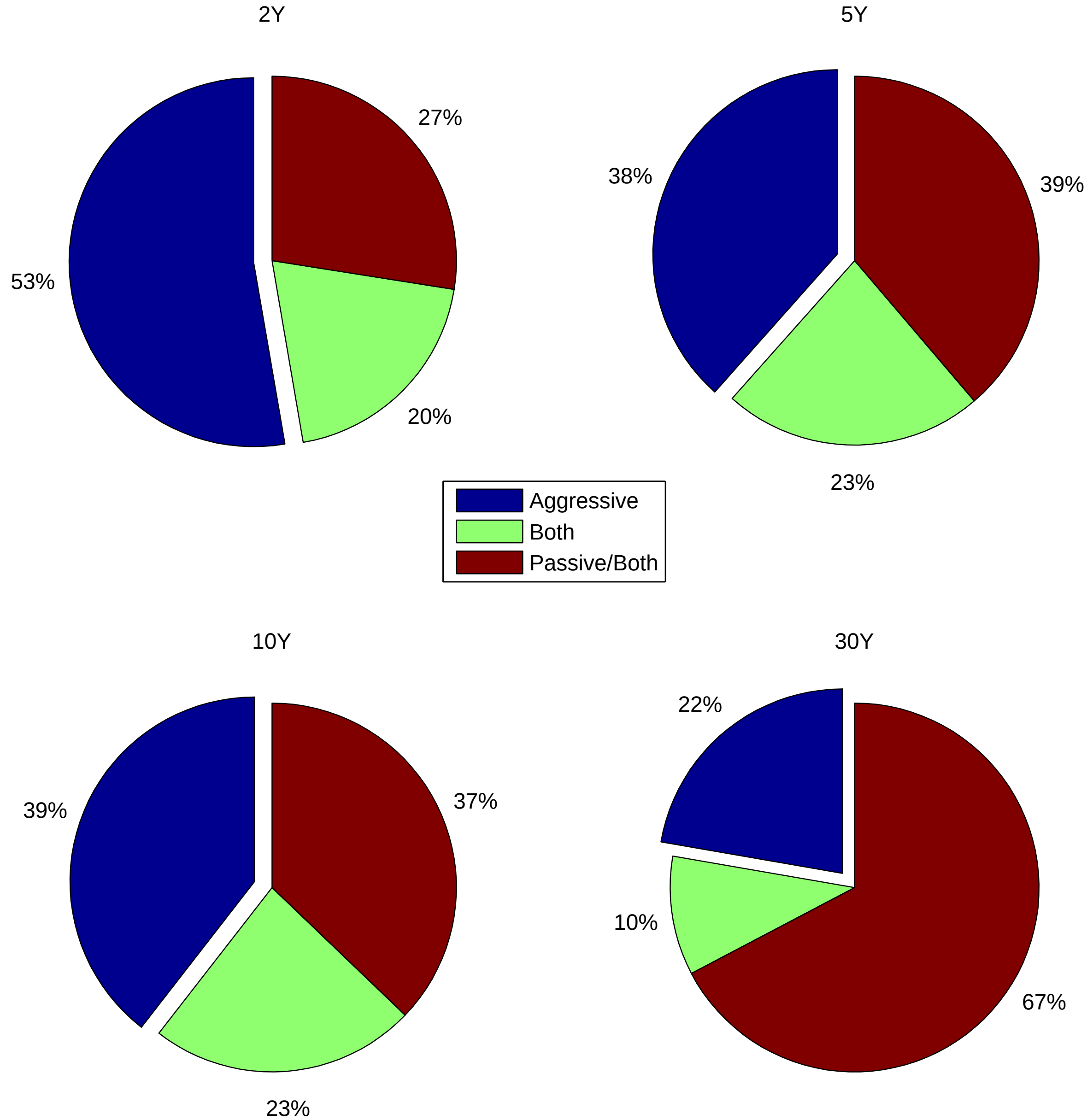
This figure shows the monthly share of transactions with workups (upper plot) and monthly share of volume transacted in workups (lower plot). The numbers are first calculated daily for the on-the-run 2-, 5-, 10- and 30-year Treasury securities on the BrokerTec platform and then averaged across days by month. The sample period is 2006-2011.

Figure 2: Intraday Pattern of Workup Probability



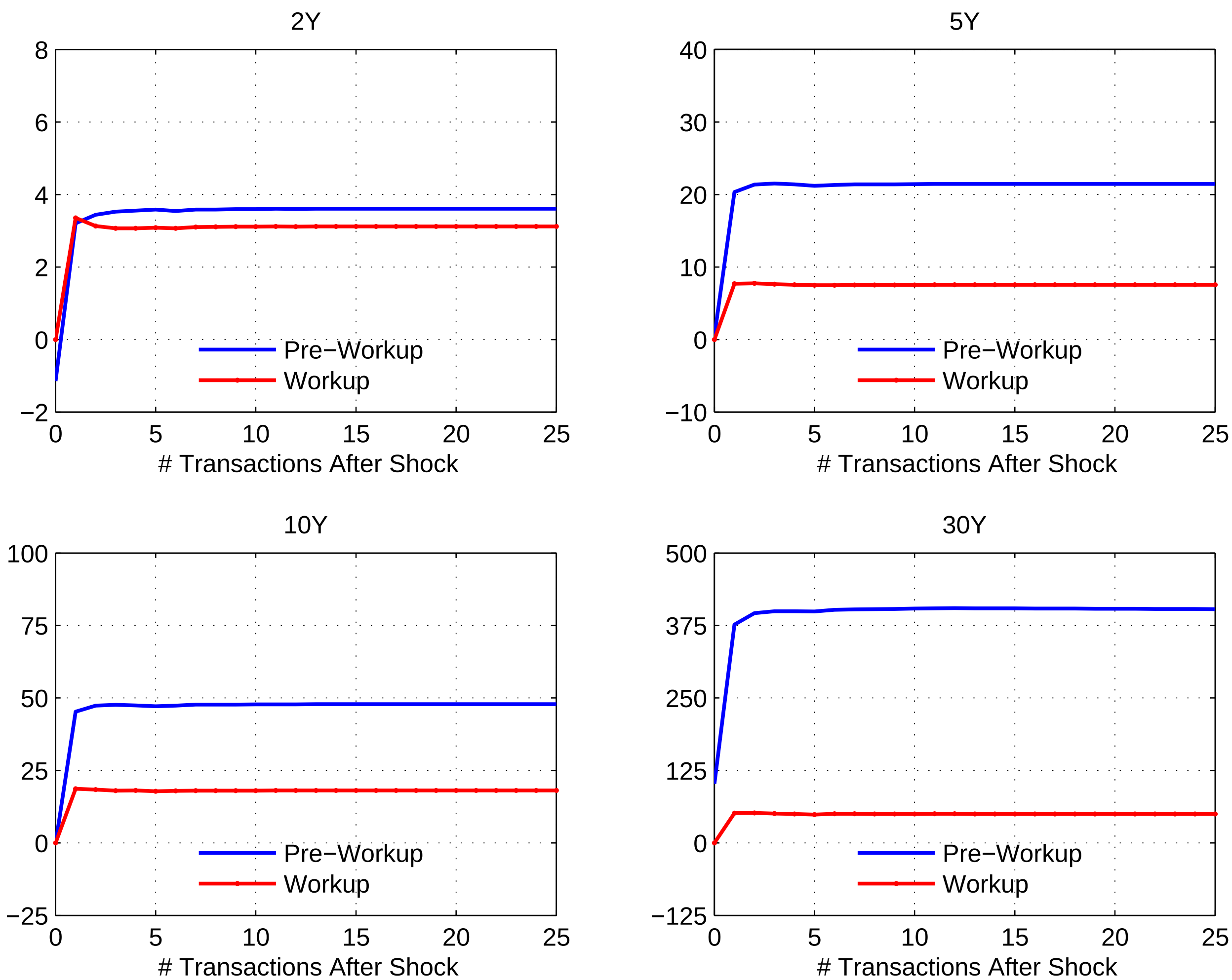
This figure shows the pattern of workup usage over the global trading day (Eastern Time). The plot starts at 18:30 of the previous day and ends at 17:30 of the current day. The numbers are first calculated for a given interval and day for the on-the-run 2-, 5-, 10- and 30-year Treasury securities on the BrokerTec platform and then averaged across days. The sample period is 2006-2011.

Figure 3: Which Side Do Workups Expand?



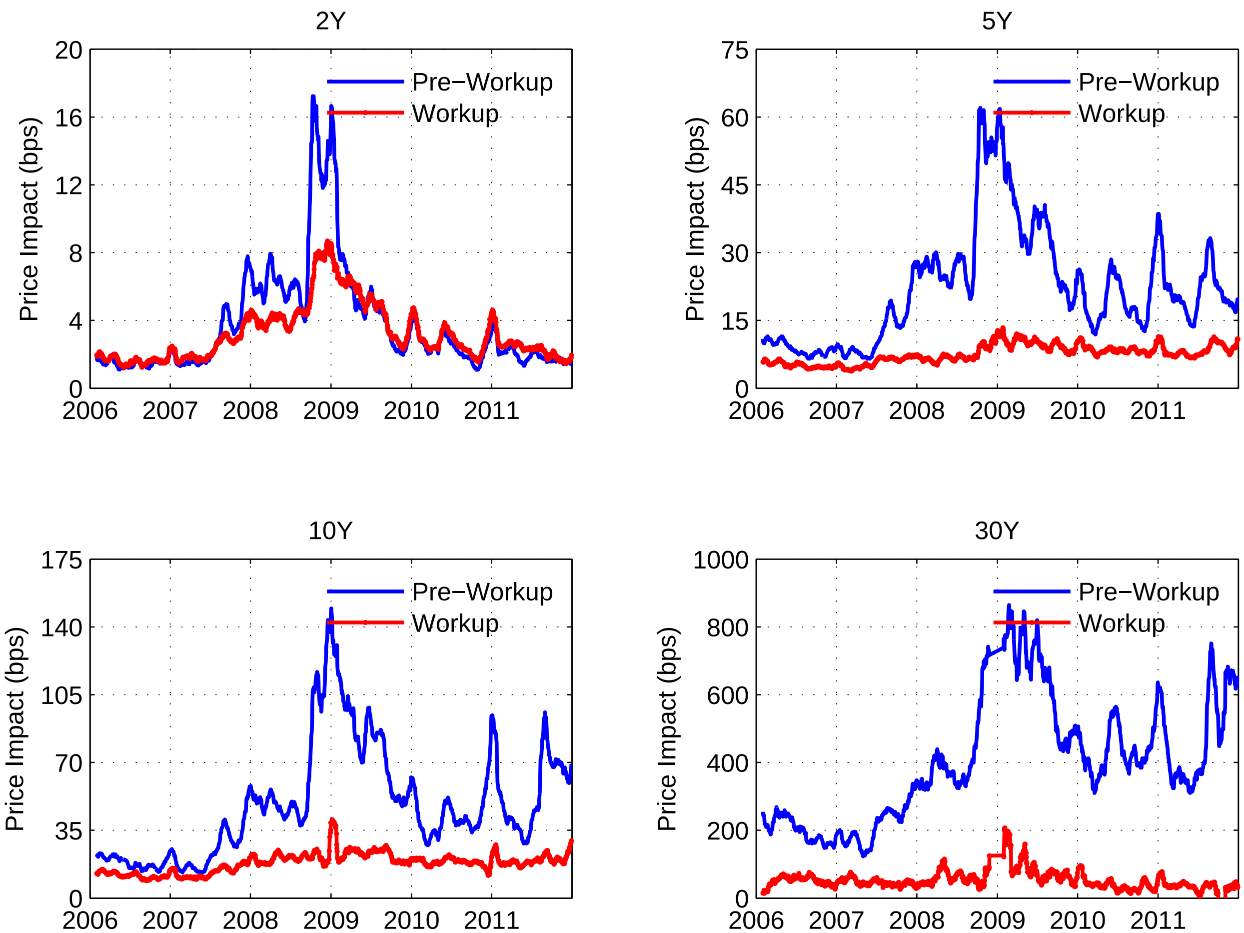
This figure shows the percentages of workups that expand volume on: 1) the aggressive side only, 2) both sides, and 3) the passive side. A workup expands only the aggressive side if the total transaction volume (pre-workup and workup volume combined) is not greater than the depth posted in the limit order book immediately before the transaction. A workup expands both sides if the pre-workup volume is less than the posted depth, but the total transaction volume exceeds the posted depth. A workup expands the passive side if the pre-workup trades exhaust the posted depth. This expansion of the passive side includes instances where the aggressive side is also expanded during the workup. The percentages are first calculated daily for the on-the-run 2-, 5-, 10-, and 30-year Treasury securities on the BrokerTec platform and then averaged across days. The sample period is 2006-2011.

Figure 4: Cumulative Impulse Response of Price to Trade



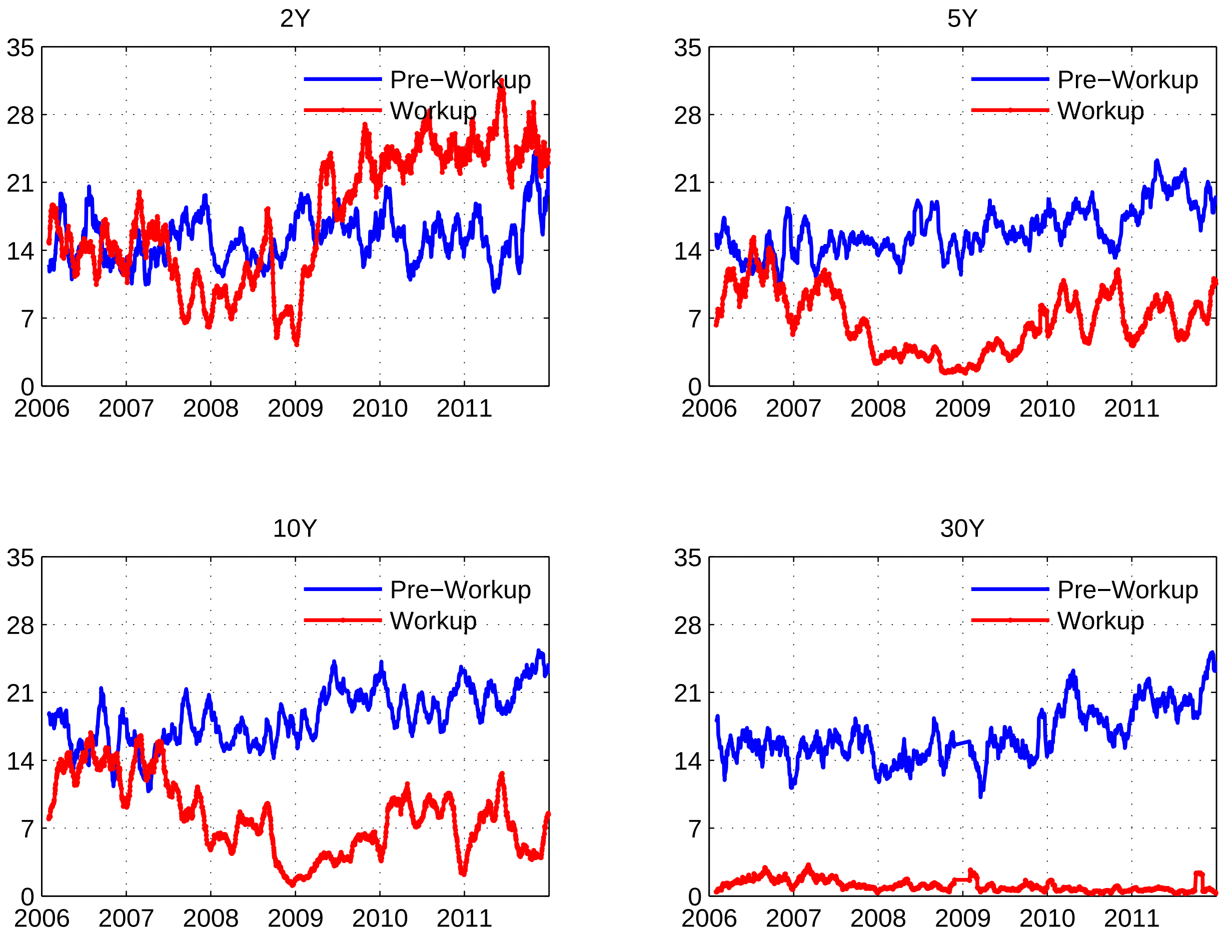
This figure plots the cumulative midpoint return (in basis points) in response to a $1 billion shock to pre-workup and workup trading volume respectively, based on a VAR(5) model of return and segmented order flow. Estimation is first done daily based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities and then averaged across days. The sample period is 2006-2011. Observations outside the [7:00-17:30] time window are excluded from model estimation.

Figure 5: Permanent Price Impact of Trade



This figure plots the 20-day moving average of the price impact of $1 billion buyer-initiated volume transacted during pre-workup versus workup phases. The price impact measures are first computed daily from a VAR(5) model of return and trade flows, and then averaged over rolling 20-day intervals. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006-2011. Observations outside the [7:00-17:30] time window are excluded from model estimation.

Figure 6: Information Share of Pre-Workup and Workup Order Flow



This figure plots the 20-day moving average of the information share of pre-workup versus workup order flow, using Hasbrouck (1991)'s information share approach. The information share measures are first computed daily from a VAR(5) model of return and trade flows, and then averaged over rolling 20-day intervals. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006-2011. Observations outside the [7:00-17:30] time window are excluded from model estimation.

A Economic Announcements

We consider three categories of news that are relevant for the Treasury market:

A.1 Macroeconomic Announcements

The macroeconomic announcements we consider are those classified as "Market Moving" indicators by Bloomberg: 1) Employment Report, 2) Consumer Price Index, 3) Durable Goods Orders, 4) GDP, 5) Housing Starts, 6) Initial Jobless Claims, 7) Personal Income and Outlays, 8) Producer Price Index, 9) Retail Sales, 10) Trade Balance, 11) Industrial Production, 12) Existing Home Sales, 13) ISM Manufacturing, 14) New Home Sales, and 15) Philadelphia Fed Survey.

A.2 Monetary Policy Announcements

The monetary policy announcements included in our analysis are FOMC rate decision announcements. Such announcements typically occur after regularly scheduled FOMC meetings, of which there are eight per year. In addition, there were rate changes announced after unscheduled meetings on two occasions during our sample period, on January 22, 2008 and October 8, 2008.

A.3 Treasury Auction Result Announcements

The Treasury auction results we consider are those for the 2-, 5-, 10- and 30-year fixed principal Treasury securities. Auction results are announced shortly after the auction close on auction dates for a given security. The 2- and 5-year notes are newly issued every month. The 10-year note is newly issued every quarter, with reopenings in the following month and – since November 2008 – two months. Starting in May 2009, the 30-year bond is also on a quarterly issuance cycle with two reopenings. For the 2006-2008 period, the 30-year bond was newly issued once a year with irregular reopenings.